FINAL REPORT

TECHNICAL PROCEDURES FOR THE WATERSHED EROSION ASSESSMENTS
C.I.P. NO. 485-617-2000

for the

City of Austin DRAINAGE UTILITY DEPARTMENT

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September, 1997

EXECUTIVE SUMMARY

With the knowledge of new urban development greatly accelerating stream channel erosion as a result of the increase in frequency, duration and peak flow in channels, the City of Austin, Drainage Utility Department requested Raymond Chan and Associates, Inc. (RC&A) to prepare this **Technical Procedures Manual** as a guideline for the completion of the **Watershed Erosion Assessments** for seventeen watersheds. The Watershed Erosion Assessments will be one component of a watershed master plan for each watershed.

Erosion Process

Preliminary stream reconnaissance have been undertaken on Blunn, Fort Branch, Tannehill Branch, Shoal, Johnson, Waller, Barton, Walnut, Harper's Branch, Country Club, West Bouldin, East Bouldin, and Buttermilk Creeks and a more detailed synoptic level survey has been completed on Williamson Creek. All of these channel systems have experienced major flood flows over the last 30 years. Two major flows, estimated to be in the order of 20<Return Interval (RI) <25 years and RI≈10 years, based on an analysis of USGS data, occurred in 1981 and 1991, respectively. Flow depths exceeded the active and inset channels in both cases. In a catastrophic system, the inset channel morphology (minor system) would likely have been significantly reworked or washed out. However, geomorphic evidence, including the presence of riparian structures and trees greater than 30 to 40 years in age on the terrace and along the active channel riparian zones, suggests that the inset channels are relatively stable in their hydraulic and planimetric form in these watersheds. Consequently, these data indicate that the morphology of the active channel in streams in the City of Austin may be controlled by the minor system flows following urbanization.

Therefore stream channel morphology within the City of Austin appear to behave in a manner which is consistent with regime theory. The geomorphically dominant events appear to range from the 1- to 5-year storm events for non-urban reaches (this range may increase to 5- to 10-year events for rock controlled channels formed in massive limestone) to RI<<1.001 years for urban systems. The geomorphic significance of the less frequent flow events in non-urban systems appears to be due to high initial hydrologic losses which effectively eliminate runoff from frequent storm events. The process of urbanization results in a fundamental shift in the flow regime due to the decrease in hydrologic storage (abstractions) and the decrease in basin response time. The result is a significant increase in the frequent, or minor system flow events. The increase in flow magnitude and frequency is such that these events become the geomorphically dominate events.

The impact of urbanization on the flow regime is greatest for the minor system flow events, which are described as the mid-bankfull to bankfull flows in in-regime streams. As a watershed develops, the associated increase in instream erosion potential results in significant enlargement of the stream channel. This enlargement may occur through erosion of the bed (downcutting) and/or erosion of the channel banks (widening) depending upon the relative erodability of the least resistant bank toe stratigraphic unit and the bed.

Commensurate with this erosion is an increase in the capacity of the channel to contain larger flows. This starts a positive feedback process in motion in which the greater flow capacity is translated into even higher instream erosion potential causing the channel to further enlarge thereby increasing its flow capacity further and so on. The process of downcutting will continue until the channel encounters a material which is more resistant relative to the least resistant bank toe stratigraphic unit or until the bed armors itself in a manner sufficient to resist further downcutting. The channel then preferentially widens until the erosive power of the prevailing flows is insufficient to erode the banks. Within this enlarged active channel the flows associated with the more frequent flood events begins to concentrate and an inset channel begins to form. As the incipient active channel evolves, it may develop into a single thread channel with a well developed meander geometry. Migration of the incipient active channel within the enlarged pre-development active channel will result in the continued enlargement of this channel. As the pre-development active channel continues to enlarge, the geomorphic significance of rare flood flow events diminishes until the geomorphic dominance of the frequent flood flow events is re-established. At this point the enlarged pre-development active channel may be considered to be an incipient floodplain channel. This process is referred to as 'valley formation' and is evident in many of the older developed watersheds within the City of Austin.

In summary, the primary factors involved in the stream erosion process are:

- basin area;
- the temporal variability, rate and volume of discharge;
- the quantity, particle size and temporal characteristics of the sediment load;
- the resistance of the boundary materials (particularly the bed materials and the least resistant bank toe stratigraphic unit);
- the type density and spatial distribution of riparian vegetation;
- longitudinal valley gradient;
- the magnitude, timing and distribution of the disturbance through the watershed;
- the time from cessation of the disturbance;
- the spatial scale of fluvial features characterizing the fluvial system; and,
- the relaxation time of these features.

This report discusses in detail the tasks to be performed to complete the above analyses to estimate the channel enlargement in the studied watersheds. Channel enlargement predictions will be based on impervious cover and geomorphic surveys to develop a relationship between impervious cover and channel enlargement. The City of Austin prepared impervious cover data for the existing and future (year 2040) conditions. The following major tasks are described in this document:

- Stream Inventory
- Erosion Problem Identification
- Hydrologic Change as a Result of Urbanization
- Prioritization Systems for Property Protection and Channel Restoration
- Delineation of an Erosion Hazard Indicator
- Knick Point Identification and Management Strategies
- Identification of Potential Meander Migration Problems and Several Bends
- Channel Enlargement and Sediment Yield
- Watershed Mapping and Photographs
- Recommendations to Manage Stream Erosion.

The above tasks will be performed to complete a watershed erosion assessment report serves as a planning tool to identify the existing and future potential erosion problems, estimate channel bank enlargement, and predict the sediment yield as a result of channel erosion.

TECHNICAL PROCEDURES MANUAL FOR WATERSHED EROSION ASSESSMENTS

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1.0 INTRODUCTION

Most of the Austin's watersheds, including urban and suburban watersheds, are drained by streams that exhibit existing creek bank erosion problems and have the potential for future creek bank degradation. The concern for future creek bank failures, long term channel degradation, and their impact to creekside residents and water quality initiated the City of Austin Drainage Utility Department to authorize the city wide watershed erosion assessments in January 1997. As directed by the City, the following tasks will be performed to identify the stream condition, predict the stream's response to urbanization, and suggest recommendations to manage the erosion processes in Austin's primary watersheds.

The purpose of this report is to document the individual tasks, their supporting theories and respective approaches and outputs for use in preparing each watershed assessment report. The City limited the study scope to watersheds and tributaries that have at least 640 acres of contributing drainage area.

The tasks identified in the Table of Contents will lead to the development of an erosion report for each watershed that summarizes the findings of the study and develops recommendations to manage the erosion processes. Each watershed report document will assist the City of Austin in managing flooding, erosion, water quality and maintenance of the creek in a coordinated and cohesive fashion that benefits the residents and users of the studied Creek watershed. A "bullet and table" format will be used to in each watershed report to allow water program managers to quickly locate the desired information for their use in implementing watershed improvement programs and projects.

1.1 REPORT SCOPE

This report has been prepared by RC&A, in conjunction with fluvial geomorphologists under the Stormwater Management Rotational List Contract executed in 1995. Aquafor Beech Limited prepared the report sections concerning geomorphic analysis and geomorphic field applications. This report was prepared to document the processes involved in the completion of each task, task purpose, the desired technical output from each task, and the presentation approach in each watershed erosion assessment report. The technical procedures will not be listed in each watershed erosion assessment, therefore this document will serve as the reference manual to the individual watershed erosion assessments. Most report sections (which document a task) shall be organized in the following format:

Task Purpose (about one paragraph)

Approach (discussion, references, backup papers, etc.)

Output (what is accomplished and how is it used in the study, about one paragraph)

Forms used to note data or prepare calculations

Example of tables to be provided in each report (headings)

1.2 Project Team

The project team and their respective roles are shown below.

Consultant Team

- Raymond Chan and Associates, Inc. - Lead Engineering Consultant, Project Management
- Aquafor Beech Limited - Regime and Non Regime Theory Application, Recommendations

City of Austin

- Project Manager: Gerry Clayton, Drainage Utility Department
- Technical Support: Pat Hartigan, Mike Kelly, Drainage Utility Department
- Erosion Management Team, Drainage Utility Department

2.0 STREAM EQUILIBRIUM CONCEPTS

Purpose

This section provides discussion on stream regime theory and the application to streams in the Austin region.

2.1 INTRODUCTION

Case studies documenting the impact of urban development on stream channel morphology yield a wide range in channel response. Variations in stream channel cross-sectional area have been observed to range from more than a 20% reduction to an increase of an order of magnitude. The dominant morphological discharge has been reported to vary from low flows to extreme events. Various case studies and related research were reviewed in this discussion in an attempt to establish a systematic method of interpreting this wide range of observations and assessing their applicability to stream channels within the City of Austin. It was apparent from this review that two types of channel systems can be described under non-urban hydrologic regimes: those whose morphology is related to the principle that most geomorphic work is performed by relatively frequent flow events; and, those whose morphology is controlled by catastrophic events. It was noted that the process of urbanization significantly modifies the prevailing sediment-flow regimes for both channel types such that frequent flood flow events become the dominant morphologic agent in small basins. Further, a thesis regarding the evolution of the channel system in response to an alteration of the prevailing sediment-flow regime associated with the process of urbanization is described.

2.2 CASE STUDIES

Lazar (1978) suggested that any change in land use (say from forest to golf course) which increases runoff yield can lead to an increase in channel erosion, the magnitude of which is highly variable, but is generally related to stream slopes and the type and amount of land use changes. Ferguson (1996) noted severe aggradation associated with deforestation and the development of agriculture in Piedmont streams in Georgia. The impact of deforestation on channel form through fires or logging activity is also well-documented (Schumm and Lichty, 1963; Orme and Batey, 1971). The transition in vegetation from meadow to forest was found to cause active bank erosion and channel enlargement due to the suppression of thick grass turf by forest and, secondly, by log jams (Murgatroyd and Ternan, 1983). Buttle (1995) also found afforestation to have a significant impact on stream form. The alteration of basin storativity associated with urbanization and the associated adverse effects of the acceleration of instream erosion processes within and downstream of developing areas has also been regarded with concern.

The initial impact of urban development is related to the accelerated erosion of the landscape due to denuding and disruption of the earth's surface by construction activity

(Savini and Krammerer, 1961; Mansue and Anderson, 1974). Gregory and Walling (1960) recorded sediment loads to a receiving stream during periods of active building that were 2 to 10 times (and up to 100 times) sediment concentrations observed during undisturbed conditions. These findings were substantiated by Keller (1962) who observed that high sediment discharge from urbanized land continued for a long period, citing, as an example, a 6-fold increase in sediment concentrations on the northwest branch of the Anacostia River. This increase in sediment load is believed to result in aggradation in the stream channel where stream sediment transport capacity is insufficient to remove the additional load. Aggradation produces a rise in bed profile and a concomitant rise in stage. To maintain the same capacity Keller (1962) argued that the stream must widen through bank erosion.

Guy and Ferguson (1962) put forward a hypothesis that instream sediment deposition following urbanization was likely the result of channel widening caused by an increase in the rate and volume of water discharge from the more impervious post-development surface. However, sediment deposition following urbanization does not occur in all cases and no clear relationship emerged in the study. They also cautioned that *"the theory for understanding the nature and complexity of urbanization-induced sediment problems has not been established"*.

In a major treatise on the topic of urbanization and stream channels, Wolman (1967) concluded that *"the process of urbanization constitutes a major disruption of prevailing conditions on a watershed"*. Using geomorphic evidence to support his theory, Wolman combined the fore mentioned concepts into the following scenario:

A) Construction activity results in aggradation leading to a choking of the stream channel.

B) Following development, the flows increase in rate and volume whereas sediment loads actually decrease as the surface becomes more impervious and the remaining denuded areas are stabilized with vegetation.

This scenario was supported by the work of Graf (1975) in a case study of Meadow Hills, Denver, Colorado. He noted that the initial land forms within the channel tended toward equilibrium under undisturbed conditions while development of the watershed from rural to urban land use resulted in an increase in flow and sediment discharge to the stream, resulting in aggradation. However, Guy (1970) concluded that while sediment is a widely-recognized pollutant and that severe sedimentation problems have been observed during construction, the actual effect on channel morphology depends upon the dilution and transport capacity of the affected stream. Further, Guy noted that the impact of urbanization on channel form may be short-lived. While this statement appears to apply to larger watersheds, Hammer (1972), in a comparison of 78 small (1.6 to 15.5 km^2 (1 - 6 mi^2)) urban and non-urban streams in the Philadelphia region, noted that channel cross-sectional area increased following urbanization. He also noted that the enlargement ratio varied with different land use types and that the influence of impervious development on channel erosion depended on the topographic characteristics of the watershed, the location and age of the development within the watershed and the type and degree of man-made drainage channels.

The hypothesis that natural stream channels enlarge as a result of increased flows following urbanization was tested by Hollis and Luckett (1976) on 32 rural and 27 urban basins in West Sussex and Canon's Brook, Harlow, Essex (U.K.). Watershed areas for the West Sussex study varied between 0.4 (0.16 mi^2) and 86 km^2 (33 mi^2). The study demonstrated that a 10 percent paving of a basin should increase channel size downstream by a factor of 1.7. However, the ratio of channel cross-sectional area for urban/rural conditions varied between 0.235 and 5.169 with a median of 1.11 and quartile values of 1.737 and 0.633. A channel enlargement of less than unity demotes a reduction in channel cross-sectional area resulting from urbanization. Unfortunately, data pertaining to basin area, physiology, the land use type and distribution, topology, boundary material erodability and channel hydraulic geometry data for individual watersheds were not provided in the study. Consequently, it is difficult for the reviewer to interpret these findings.

Various measures of central tendency for Canon's Brook, described as a clay catchment with an area of 21.4 km^2(8.2 mi^2), indicated that the increase in channel size (by a difference in means test suited to paired observations) could not be confirmed even following a paving of 18% of the basin. These data indicate that infilling of the channel may occur in response to urbanization in some instances. This finding was supported by observations of Watts Branch, a 9.6 km^2 (3.7 mi^2) basin near Rockville, Maryland wherein stream channel cross-sectional area actually reduced and, 20 years after urbanization, the cross-sectional area still remained 20 percent less than the original area (Leopold, 1973). The infilling of the channel may be related to a change in the timing characteristics of the contributing tributaries (*e.g.* urban development in the lower portion of the watershed may actually reduce anticipated high flows because of the slower response time of the upper undeveloped portion of the watershed).

These studies serve to indicate that a wide range in morphological response may be anticipated in association with development of a basin. Part of the variation observed in channel response to urbanization may be attributed to differences in basin area as well as the type and distribution of development within the basin. The perviousness of the soils may also be a factor. As reported in *Regulatory Approaches to Manage Stream Erosion (Hegemier, MacRae)*, it was found that the alteration of the hydrologic regime was more pronounced for basins with highly pervious soils than for clayey soils with low infiltration rates. This effect may be amplified in arid regions where large losses reduce or eliminate overland flow to the Creek for frequent flow events (Recurrence Interval (RI) less than 1:2 years). A continuous modeling analysis for streams in Ontario demonstrated that a urbanization may increase the occurrence of erosion causing runoff events by 63 times resulting in an increase in the duration of flow rates related to erosion of the channel boundary by 100 fold (James, 1987; MacRae, 1996). Major landform changes may result from these alterations in the flow regime. Urbonas (personal. comm. 1988) noted that three to five years after urbanization of Chop Creek, a small drainage system in Denver, Colorado, a channel measuring approximately 4.6 m (15 ft) deep by 30.5 m (100 ft) wide formed where none had existed before. Urbonas (1980) reported similar dramatic landform alterations for Toll Gate Creek in Aurora, Bear Creek in Boulder, Little Dry Creek in Arapahoe County and Sanderson Gulch in Denver, Colorado. The enlargement was associated with frequent summer storms where virtually no flows existed prior to urbanization. Examination of a flood frequency curve for a 40 ha (100 acre) residential area illustrated that a 1:2 year peak flow from the site after urbanization corresponded to a 1:10 year event prior to urbanization and the 1:100 year event increase by 2 fold.

This non-uniform increase in the flood frequency curve following urbanization is similar to but of less magnitude than that reported by Hollis (1975). In a synthesis of data from 15 references on the impact of urbanization of the hydrologic regime Hollis (1975) reported a increase in the 1:1.01 year, 1:2 year and 1:100 year events, following complete urbanization of a basin, of up to 15, 4 and 2 times flows under pre-development land use conditions, respectively, following complete development of the basins. Comparison of these observations with data reported by Urbonas (1980) for the arid region of Denver, Colorado, Booth and Anderson (1994) for steep, forested basins in Washington, and, City of Austin SOS Ordinance Defense (1994) indicate that alteration of the hydrologic regime in areas characterized by high precipitation losses (low rainfall to runoff translation for frequent precipitation events) may be more pronounced then that reported for humid areas which demonstrate a high runoff response to frequent rainfall events.

Differences in bank material sensitivity to erosion by flowing water (scour) may also be an important determinant in the explanation of channel response to a disturbance. Urbonas (1981) note large landform alterations in streams which were poorly-vegetated and formed in highly-erosive materials. Boundary material erodability is described by Osterkamp (1980) as the principle factor controlling the channel width-depth ratio. In stratified deposits channel form may be controlled by the resistance to scour of the basal stratigraphic unit. Klimek (1974), Andrews (1982) and Thorne and Lewin (1982) noted that channel banks are often composed of stratified, heterogeneous materials with the basal stratigraphic unit typically being the least resistant to scour. MacRae and Rowney (1993) in a study of seven streams in Surrey, British Columbia found that channel widening following development of the tributary area was related to the sensitivity of the least resistant bank toe stratigraphic unit relative to the bed material.

The relative erodability of the least resistant basal stratigraphic unit and the bed material represents yet another consideration in the explanation of variance noted in the above case studies. Schumm's (1971) model of valley formation states that a channel will downcut until it encounters a material which is sufficient to resist further degradation. MacRae (1991) modified this model such that the stream will downcut until it encounters a stratigraphic unit which is resistant relative to the least resistant bank toe stratigraphic unit. At this point the channel will tend to form a new floodplain through widening. Channels which enlarge principally through widening may produce a smaller channel enlargement ratio than channels which undergo a valley formation process (downcutting and widening) because the reconstruction of the floodplain at a lower elevation requires the movement of a greater amount of material. The evolution of the stream channel is discussed in the subsequent Sub-Section of this report.

Osterkamp (1980) noted that while boundary material characteristics was the principle factor controlling channel width:depth ratio, riparian vegetation characteristics (type, density and distribution), was a modifying factor. The influence of riparian vegetation, however, is complex. MacRae (1980) observed that grass lined channels associated with relatively broad, flat floodplains and having banks of less than 0.7 m (2.3 ft) were less sensitivity to a disturbance in the prevailing sediment-flow regime than the equivalent channel colonized by large, woody species. The reverse was observed, however, as bank height exceeded approximately 1.0 m (3.3 ft). Murgatroyd and Ternan (1983), noted that bank failure occurred at the transition in vegetation from meadow to forest in channels with bank heights ranging from 0.4 to 0.7 m (1.3 to 2.3 ft) as thick grass turf was replaced by forest. Dense root mats associated with grasses may actually control channel morphology for first order streams having low bank heights formed in cohesive boundary materials.

The timing of observations of channel form following urbanization of the basin and the relaxation time for the measured features to respond to a disturbance may also account for some of the variability. Hammer (1972) noted that channel hydraulic geometry may require thirty years to respond to a perturbation in the driving mechanisms associated with urban development. Although the majority of this adjustment may occur in the first 10 to 15 years, measurement over shorter time periods may underestimate the amount of enlargement which may occur.

Despite the diversity of reported responses, most case studies demonstrate that channel enlargement occurs following urbanization of a basin. Some additional studies for reference include Nanson and Young (1981), Fox (1976), and Rutherford and Ducatel (1994). One study of particular interest is that of Morisawa and Laflure (1979). This study reported findings for eleven (11) urbanizing streams (basin area ranged from 2.32 km^2 (0.9 mi^2) to 27.5 km^2 (10.6 mi^2), under mixed land use located near Pittsburgh and Monroeville, PA and Binghampton, NY. All stream banks have gravel-pebble beds with some silt and cobbles, while bank materials are generally composed of stratified gravel, sand and silt. They observed that channel cross-sectional area began to enlarge after approximately 25% of the basin exceeded 5% impervious cover. Assuming that development is concentrated within subdivisions and using a percent imperviousness of 40 to approximate mixed land use conditions, this translates into an increase in imperviousness of 10 percent. Similarly, Booth and Anderson (1994) noted that a threshold of approximately 10% change in imperviousness demarcated stable from unstable channel systems in western Washington.

Morisawa and Laflure (1979) also demonstrated that channel enlargement increased in a non-uniform manner with increasing basin imperviousness. The initial lag in response may be associated with a threshold condition after which channel enlargement increases greatly. Secondly, they observed that each stream adjusted bankfull geometry in response to downstream increases in discharge in a distinctive way and that the mode of adjustment within any one stream varied through time as development progressed through the watershed and the stream adjusted its form. In general, they reported an increasing rate of channel enlargement in the downstream direction although this was complicated in some streams due to sewering and riparian structures. The relevance of the Morisawa and Laflure (1979) enlargement curve to Austin streams is discussed in the concluding Sub-Section of this chapter of the report.

The above studies have dealt with alluvial stream channel systems. However, rock-bed control systems have also been studied and found to behave in a similar manner. Allen and Narramore (1985) examined 65 streams formed in massively bedded chalk and uniformly laminated shale materials of the Blackland Prairie Physiographic Province of Texas. Bank materials for the Austin chalk are comprised of silty clay interbedded with continuous lenses of angular chalk gravel. The channel bottoms are cut into the chalk bedrock. The banks of the shale streams are composed of weathered shale and clay alluvium. The channel bed is worn into the shale bedrock which is covered with a thin veneer of clayey alluvium in some instances. They observed enlargement ratios (R_E) of 2.4 and 1.7 for the chalk systems and 1.9 and 1.75 for shale systems with watershed areas of 2.6 km^2 (1 mi^2) and 26 km^2 (10 mi^2), respectively, following complete development of the basins. These creek systems are typical of many of the reaches found in the Blackland Prairie physiographic regions within the City of Austin.

MacRae et al., (1994) reported a channel enlargement ratio of 2.1 for Sawmill Creek, Mississauga, Ontario (8.6 km^2 (3.3 mi^2); a rock-bed control systems formed in the thinly bedded, interbedded shale-limestone of the Georgian Bay formation) following 50% development of the watershed under primarily medium density residential land use. Development, which began in 1977, is still ongoing. Consequently, the adjustment process is incomplete and further enlargement of the channel is anticipated. Cooksville Creek, Mississauga, Ontario (33 km^2 (12.7 mi^2)), also located in the Georgian Bay formation, has been undergoing development in a fairly continuous manner since 1954. The basin is currently 85% developed. Based on data reported by Triton et al., (1996), this watershed has enlarged by approximately 3 times to date in the downstream portion of the channel system. Triton (1996) concluded that urbanization and natural migration processes were responsible for the observed instabilities which have been aggravated by instream works. Stormwater Management practices may also have inadvertently contributed to the de-stabilization of the urbanizing stream channels (McCuen, 1979; McCuen and Moglen, 1988; MacRae, 1991).

The results of these and other studies serves primarily to document the wide variation in the response of channel form, as measured by channel hydraulic geometry, due to an alteration in the driving mechanisms controlling channel form associated with the process of urbanization. Collectively, these studies have lead to a better appreciation for the complexity of the relationship between river channel form, the prevailing hydrological and sediment regimes within the watershed and the nature of the bed-bank materials. The key factors identified were:

- basin area;
- the temporal variability, rate and volume of discharge;
- the quantity, particle size and temporal characteristics of the sediment load;
- the resistance of the boundary materials (particularly the bed materials and the least resistant bank toe stratigraphic unit);
- the type density and spatial distribution of riparian vegetation;
- longitudinal valley gradient;
- the magnitude, timing and distribution of the disturbance through the watershed;
- the time from cessation of the disturbance;
- the spatial scale of fluvial features characterizing the fluvial system; and,
- the relaxation time of these features.

The following discussion attempts to provide a framework for the interpretation of the responses reported in the above case studies and the key factors noted above.

2.3 FLUVIAL SYSTEM RESPONSE TO URBANIZATION

The wide range in response by the active channel to the process of urbanization, as cited above, implies that natural channels vary significantly in their overall susceptibility to changes resulting from the alteration in land use. Unfortunately, *"the capacity to adequately determine whether a river is susceptible to a river-form change has not been established"*, and *"the capacity to determine when a river-form change will occur does not exist..."* (Burkham, 1981). The problem arises from the complexity of the erosion and sedimentation processes in that an adequate accounting for the timing and discontinuities involved in these processes is presently not possible except in a probabilistic or general manner. This is because the physical laws governing erosion and sedimentation processes are incompletely known (ASCE, 1982). This does not mean that river systems can not be managed, it means that the study of river channels is an imprecise science.

The reason for this lack of quantitative rigor is that alluvial rivers are complex, dynamic, process-response systems in a constant state of flux. First of all, the fluvial system may be described as being composed of variety of features ranging in spatial scale from micro-forms (features of the scale of secondary currents and localized perturbations in the flow), to meso-forms (features of the scale of the channel width), to macro-forms (features of the scale of many channel widths or the floodplain (Lewin, 1978). Secondly, these features are inter-related, but their relaxation times may vary from $10^{-6}<t_R<10^{1}$ years for micro-forms, to $10^{1}<t_R<10^{1.7}$ years for meso-forms, to $10^{2}<t_R<10^{3}$ years for macro-forms (Lewin, 1978; Hammer, 1972; Knighton, 1987). Thirdly, meso and macro scale forms may lag in their response to a change in the driving mechanisms due to the existence of geomorphic thresholds (Morisawa and Laflure, 1979; Henderson, 1966; Schumm and Beathard, 1976; Chang, 1985). Consequently, a perturbation in the driving mechanisms controlling channel form may manifest itself at various spatial and temporal scales.

Fourthly, alluvial channels have two free boundaries which may be adjusted simultaneously in response to a disturbance. Fifthly, channels tend to be formed in heterogeneous materials which respond as individual particles or as collections of particles. Finally, localized perturbations in flow turbulence caused by peculiar rocks or the deflection of flow by debris in the channel, can create significant localized variations in channel form.

Thorn and Welford (1994), describe possible conceptual response models which include:

- no alteration in form under a small disturbance (*neutral equilibrium*);
- temporary alteration in form wherein the system returns to its former state following cessation of a small disturbance (*stable equilibrium*);
- permanent alteration in channel form following a small disturbance without achieving stable behavior at a new equilibrium position (*unstable equilibrium*); and lastly,
- no alteration in channel form following a small disturbance but larger perturbations result in alteration of the system followed by stable behavior in a new equilibrium position (*metastable equilibrium*).

Within this description of equilibrium positions, it possible that a fluvial system may exhibit more than one equilibrium position; the path between equilibrium positions may be smooth or abrupt (catastrophic); and, systems starting in identical positions may follow different pathways to divergent equilibrium positions.

Exactly how the system performs depends upon a dynamic adjustment between the ability of stream flow to perform work, the capability of the stream channel to transport its sediment load and flow through mutual adjustment of channel roughness, hydraulic and planimetric form geometry, and the magnitude and spatial and temporal distribution of the disturbance. In describing this process-response system in a deterministic manner, there are more unknowns then equations. Consequently, approximations of the behavior of the system are employed to reduce the problem to a manageable form.

The premise governing many engineering approaches to river form is that a river is in a state of *metastable equilibrium*, referred to as *"in-regime"*. That is, river form develops in response to a continuum of flow events such that the dimensions of the active channel are in accord with the events which perform the most work as measured by the product of the mass of sediment moved by an event of given return period and the frequency of occurrence of that event (defined as the "effective work curve"; Wolman, 1960; Leopold et al., 1964). Although large, catastrophic events (recurrence intervals of RI approximates 100 years) are capable of performing considerable work, they have a low frequency of occurrence and the total amount of work performed is relatively low. Similarly, smaller events (RI<1.01 years), which occur frequently, have a low capacity to perform work and consequently, the total amount of work performed is also relatively low. Leopold et al. (1964) and Leopold (1968) noted that active channel hydraulic geometry is in accord with events of 1.5 <RI <2 years and that these events correspond to the maximum point on the effective work curve.

Leopold et al., (1964) also observed that the range of geomorphically significant flows lie between the lower limit of competence and an upper limit established as those flows which are no longer contained within the active channel. As previously noted, studies by Hollis (1975) and Urbonas (1980) showed that the increase in runoff rate due to urbanization is non-uniform such that the increase in flood frequency diminishes with return period. MacRae and Rowney (1992) demonstrated that this non-uniformity causes the maximum point on the effective work curve to shift toward the mid-bankfull events - those events that occur less then once in every year, but are above the level of competence. James (1995) observed for streams in Scarborough, Ontario that the geomorphically dominant flows may be in accord with events of 2 to 3 month frequency following urbanization in regions experiencing intense rainfall events. These data are consistent with computations on the hydrologic effects of urbanization reported in Section 6 of this report. These studies indicate that mid-bankfull flow events are the events which do the most work in *metastable equilibrium* streams in urban environments, and consequently, they represent the geomorphically dominate flow events.

The *metastable equilibrium* system maintains a stable behavior as long as the stresses applied to the system are relatively small, that is they are within certain geomorphic thresholds. This behavior has given rise to the term *dynamic equilibrium* which incorporates notions of steady state. The term *dynamic equilibrium* refers strictly to the relationship between processes that are adjusted to one another by means of negative feedback mechanisms (Ahnert, 1993) and steady state refers to the concept of conservation of mass, e.g. the mass into and out of a specified reach are equal (Thorn and Welford, 1994).

Regime theory and hydraulic geometry concepts are predicated on this concept of *dynamic equilibrium*. However, if forces acting on the system exceed the geomorphic thresholds in a metastable system, then geomorphic change occurs toward a new equilibrium position. In the case of urbanization, the disturbance represents a fundamental, and on-going shift in the driving mechanisms controlling channel form. Consequently, a fluvial system under *metastable equilibrium* behavior would evolve toward a stable behavior at a new equilibrium position. This evolution, however, can be either catastrophic or smooth and it may be complicated by the relaxation time for recovery of fluvial forms of various scales, local heterogeneity's in the system, the propagation of knick points and instream works.

By way of illustration of smooth or catastrophic behavior of *metastable equilibrium* streams assume that such a system is currently behaving as a stable system and that it is exposed to a disturbance that exceeds the threshold for stability at the existing equilibrium position. Further, assume that this disturbance results in a permanent alteration of the prevailing flow regime. The initial response is to increase flow velocity which leads to an increase in competence and subsequently to an enlargement of the channel. The enlargement may occur through downcutting, widening or both depending upon the erodability of the boundary materials. The increase in channel cross-sectional area translates into a higher conveyance capacity. The larger flows, in turn, increase stream competence which results in additional enlargement of the channel cross-sectional area.

This positive feedback mechanism continues until the stream has enlarged to the point where flow velocities are no longer sufficient to erode the boundary. Since the majority of the enlargement process is typically complete within 20 to 30 years, with most of the enlargement occurring within the first 10 to 15 years, then a relatively smooth adjustment period can be envisioned provided no rare flood events occur during this period. If a rare flood event were to occur it is reasonable to expect that the de-stabilized channel will respond through a catastrophic enlargement of the channel system. In this regard, all geomorphic systems are susceptible to catastrophic behavior (Wolman and Miller, 1960) , if the force applied to the system exceeds its threshold for stability.

Stevens et al., (1975) noted that rivers have a memory in that their form is dependent on events presently occurring and on extreme flood events which may have occurred in the distant past. A knick point, such as a scour hole associated with turbulence caused by a localized perturbation in the flow field, can propagate upstream through the channel system resulting in a significant alteration in channel form over decades to centuries. These gradual or progressive alterations in form, however, are not typical of all fluvial systems. Based on historical evidence of the effect of large floods on river form reported in the literature (Smith, 1940; Schumm and Lichty, 1963; Everitt, 1968; Wolman and Eiler, 1958; Burkham, 1972; Nixon, 1973; Graf, 1983; Finley and Gustavson, 1983), it was concluded that the in-regime concept, applicable to metastable equilibrium streams, may not be valid in some cases. These later fluvial systems are characteristic of ***unstable equilibrium*** behavior, changing their planimetric and cross-sectional form with major flood flows. Using a ratio of peak flood flow to average annual peak flood discharge as a measure, Smith (1940) concluded that for small ratios a river could be considered in-regime. Hence, regime equations describing river form would be valid for such streams. Conversely, if the ratio of the n-year flood to the average annual peak flow is large, the river should exhibit an unstable equilibrium channel form. Smith (1940) surmised that the extreme flood event, in basins experiencing a wide range in peak flow events, may be the principal agent of channel change while successive smaller events result in channel filling. These channels are referred to as catastrophic systems.

While channel morphology appears to be a related to the peakediness of the hydrologic response of the watershed other factors such as the susceptibility of the channel boundary materials to scour, the entrenchment of the channel system, the nature of the sediment load and the role of riparian vegetation must also be considered. Burkham (1981) found that the *"in-regime"* concept was valid for streams whose channel boundary was able to withstand stresses such that only minor landform alterations occurred during infrequent high-flow periods. These are typically described as being systems with small active channels (*i.e.* with insufficient capacity to contain a major flood flow) having a meander pattern and the type and extent of floodplain vegetation consistent with dominant low-flow rates. These channels are characteristics of those described by Wolman and Miller (1960) in the development of the effective work concept and Leopold et al. (1964). For such streams, Burkham (1981), noted that the correlation of annual average flow with the hydraulic geometry variables (such as width and depth at bankfull stage) was usually good because they reflect the temporal dominance of the lower frequency floods. However, Burkham (1981) also noted that a low-flow system may change rapidly to a high-flow system following a series of major flood events should the erosion potential exceed the threshold of stability for the system. He noted that the reverse process is much slower, requiring several to tens of years. Consequently, a *metastable equilibrium* channel type can be transformed into an *unstable equilibrium* system and back again given a suitable set of stresses and sufficient time. The transformation of an *unstable equilibrium* to a *metastable equilibrium* system may also be possible given the appropriate modification of the prevailing hydrologic-sediment regime.

What fluvial characteristics constitute an *unstable equilibrium* system is the subject of considerable debate. Catastrophic event systems, as described previously, are those in which the planimetric and hydraulic geometry of the channel is dictated by rare flood events with channel infilling occurring during the intervening periods. Burkam (1981), citing previous studies by Bryan (1927), Smith (1940), Schumm and Lichty (1963), Mack and Goodlette (1960), Stewart and La Marches (1967), Scott (1973) and Burkam (1972), observed that change in river channel form through natural processes in non-urban streams can be of the order of 7 to 28 times. He notes that *"...major floods apparently were a primary cause of river-form change for each of the samples cited..."*. A rationale for the dominance of rare flood events for channel systems formed in regions characterized by flashy hydrologic response in entrenched in limestone is provided by Baker (1977). In contrast, Gardner (1977) reported only minor geomorphic effects associated with a catastrophic flood on the Grand River, Ontario, Canada which is located in a humid continental climatic zone (Strahler, 1969) and characteristic of *metastable equilibrium* streams. These observations are broadly consistent with other research reported in the literature (Carlston, 1963: Collins and Schalk, 1937; Wolman and Eiler, 1958; Dury, 1973; Costa, 1974). These observations tend to support the idea contention that channel systems can be broadly categorized as being in-regime or catastrophic in behavior. How fluvial systems, such as alluvial fans as described by Beaty (1974) and braided gravel bed systems in arid is not clear. As with any attempt to classify what is essentially a complex, continuum of channel response mechanisms, these broad categories are also the subject of debate the content of which is beyond the subject of this discussion.

Fluctuations in channel form due to urban-induced erosion, as reported in the literature for in-regime streams, varied from 2.0 to 6.0 times pre-development stream channel width at bankfull flow as noted previously (Hammer, 1972; Graf, 1975; Hollis and Luckett, 1976; Robinson, 1976; Morisawa and Laflure, 1979; Allen and Narramore, 1985; MacRae et al., 1994). An examination of the flood frequency curves and flow exceedance-duration analyses, for streams in humid regions, indicate the greatest change in the flow regime associated with urbanization of a basin occurs for mid-bankfull flows of RI<1 year (MacRae and Rowney, 1993). Urban development has only a minor affect on the RI=100 year event (Hollis, 1975). Observations of the impact of urbanization on the hydrologic regime and morphology of the receiving channels of several Colorado streams, as reported by Urbonas (1981; 1988), indicate that the enlargement experienced by fluvial systems in arid climates exceeds that reported for streams in humid regions. As noted previously, Urbonas (1981) attributed the extreme morphologic response of these fluvial systems to the creation of a flashy minor system where effectively none had existed prior to urban development. Burkham (1981), also noted that rivers in arid and semi-arid regions are more susceptible to major changes in river form than those in humid temperate regions.

In the catastrophic system, flood frequency data indicate that high frequency floods (RI<2 years) rarely occur due to high precipitation losses (depression storage and infiltration). As event magnitude and intensity increase less frequent events (2<RI<5 years; Section 6.0) may generate overland flow from localized areas but not from the watershed as a whole. These events are referred to as the minor system flows and they may have a local impact on channel morphology but they lack the competence to rework the materials laid down by larger flood flow events. The low frequency floods (RI>5 years), which are referred to as the major system flows, are able to satisfy hydrologic losses and generate overland flow contributions to the stream channel on a watershed wide basis. Consequently, unit runoff rates increase along with effective drainage area as event magnitude increases from minor to major system events. Baker (1978), in a review of Wolman and Millar's (1960) effective work concept, provided a rationale for the geomorphical dominance of major system flows in small catchments experiencing intense thunderstorm activity. The concept was illustrated using Elm Creek, a small (12.5 km^2 (4.8 mi^2)) watershed in central Texas. The channel has been worn into the well-jointed Edwards and characterized as having,..."*a crude pool-riffle sequence that usually exposes the bare bedrock channel floor on the outer bends of ingrown meanders. Large blocks of dense, hard limestone (Edwards Formation) sometimes 4.5 m in diameter, are introduced on the steep cutbanks. Cliffs as much as 20 m high develop at these locations where undercutting is aided by groundwater seepage and sapping of the bed rock. Softer limestone, such as the Austin chalk, may introduce coarse particles by a bedrock spalling process that is common immediately after a flash flood. The bare-rock channel floors often contain solutional features and small inner channels that are 1 or 2 m wide and several centimeters deep*",... which are related to low flow discharges (Baker, 1978). High hydrologic losses limit the competence of the minor system flows, consequently the major system flows are the geomorphic agents for the formation of the fluvial features characterizing the system.

Elm Creek experienced a precipitation event that was estimated to have a RI>>100 years. Significant reworking of bar forms was observed in the lower portion of the basin. Channel planimetric and hydraulic geometry, however, appeared to experience only minor alteration. It is possible that Elm Creek represents *a metastable equilibrium* stream channel system whose geomorphically dominant flow event is simply shifted toward the less frequent flood flow events. In this scenario, the extreme flood flow event noted by Baker (1978), while a significant geomorphic agent, is not necessarily the geomorphically dominant flow event. Finley and Gustavson (1983), noted the geomorphic significance of a 10-year return period event in Tierra Blanca Creek downstream of Buffalo Lake in Randall County located in the semi-arid region of the Texas panhandle. The study channel is worn into moderately to slightly calichified sands and gravels of the Ogallala Formation capped by the caliche Caprock. The materials are considered to be relatively impermeable and strongly indurated. Precipitation typically occurs as thunderstorm activity, with approximately, 43 % of the mean annual precipitation of 400 to 500 mm, occurring from May to July. The combination of high imperviousness and thunderstorms yields a flashy hydrologic system resulting in periodic, intense erosion episodes which control the geomorphic evolution of the region.

Further, the minor system flows, which are essentially non-existent in semi-arid and arid regions under non-urban land use conditions, would increase significantly following urbanization (assuming traditional development forms without stormwater management controls). As noted by Urbonas (1981) the increase in flow for events of RI<2 years is infinite, the RI=2 year runoff event under urban land use conditions may equivalent to a pre-development RI=10 year event and the RI=100 years event may double under the post-development scenario. Consequently, a catastrophic event system, which is characterized by an effectively non-existent minor system, may be fundamentally altered following urbanization to a flow regime typified by a ***metastable equilibrium*** system.

2.4 STREAM CHANNEL EVOLUTION

The impact of urbanization on the flow regime is greatest for the minor system flow events, which are described as the mid-bankfull to bankfull flows in in-regime streams. In ***metastable equilibrium*** streams, these flood flow events control channel form. In ***unstable equilibrium*** channel systems, the increase in occurrence of these events is even more dramatic because of the possible absence of minor system flows prior to urban development. In such instances, the ***unstable equilibrium*** channels may evolve toward a ***metastable equilibrium*** system. In either case the associated increase in instream erosion potential results in significant enlargement of the stream channel. This enlargement may occur through erosion of the bed (downcutting) and/or erosion of the channel banks (widening) depending upon the relative erodability of the least resistant bank toe stratigraphic unit and the bed.

Commensurate with this erosion is an increase in the capacity of the channel to contain larger flows. This starts a positive feedback process in motion in which the greater flow capacity is translated into even higher instream erosion potential causing the channel to further enlarge thereby increasing its flow capacity further and so on. The process of downcutting will continue until the channel encounters a material which is more resistant relative to the least resistant bank toe stratigraphic unit or until the bed armors itself in a manner sufficient to resist further downcutting. The channel then preferentially widens until the erosive power of the prevailing flows is insufficient to erode the banks. Within this enlarged active channel the flows associated with the more frequent flood events begins to concentrate and an inset channel begins to form. This inset channel is an incipient active channel formed within the enlarged pre-development active channel. Initially the channel is a multiple thread system or single thread braided channel. As the incipient active channel evolves, it may develop into a single thread channel with a well developed meander geometry. Migration of the incipient active channel within the enlarged pre-development active channel will result in the continued enlargement of this channel. The occurrence of rare flood flow events during this period may further enlarge the pre-development active channel and rework the incipient active channel in a catastrophic manner. As the pre-development active channel continues to enlarge the geomorphic significance of these rare flood flow events diminishes until the geomorphic dominance of the frequent flood flow events is re-established. At this point the enlarged pre-development active channel may be considered to be an incipient floodplain channel. This process is referred to as 'valley formation' and is evident in many of the older developed watersheds within the City of Austin.

The process of valley formation in urban environments is complicated by heterogeneity's in the boundary materials, the upstream propagation of knick points, human intervention through the construction of riparian structures, pipeline crossings, stormwater management controls, and rock outcrops. Although the evolution of the channel toward a new equilibrium position can take hundreds to thousands of years to complete, the period of highest geomorphic activity in alluvial channels is typically within the first 5 to 10 years of the initiation of development (Knighton, 1985) and the rate of geomorphic activity approaches pre-development levels after 20 to 30 years (Hammer, 1972; Knighton, 1985). Watersheds within the City of Austin with development of 25 to 30 or more years, have reaches which demonstrate an inset channel geometry. The morphological attributes of these channel systems are described in the following section.

2.5 CITY OF AUSTIN STREAMS

Preliminary stream reconnaissance have been undertaken on Blunn, Fort Branch, Tannehill, Boggy, Shoal, Johnson, Waller, Barton, Walnut, Bull, Harper's Branch, Country Club, East and West Bouldin and Buttermilk Creeks and a more detailed synoptic level survey has been completed on Williamson Creek. The preliminary surveys involved qualitative assessments of channel form up and downstream of bridge crossings and other points of access using a Rapid Geomorphic Assessment (RGA) protocol. In addition to these qualitative observations, measurements of channel hydraulic geometry were noted at one location on each of East Bouldin and Shoal Creeks. The synoptic level survey involved the measurement of hydraulic geometry at 30 points along the Williamson Creek stream channel and its major tributaries.

The portions of these channels which have been urbanized for 20 to 30 years or more commonly demonstrated an inset channel form in reaches. This form was noted in channel systems which were not disturbed by instream works as well as those reaches where instream channel works were completed over 20 to 30 years ago. The East Bouldin basin, tributary area to Gillis Park is approximately 2.6 km^2 (1 mi^2), was essentially development out by the mid 1960's. The Gillis Park reach of the Creek was also channelized over 30 years ago as a trapezoidal channel with a flat bottom (City of Austin, South First Street Corridor TSM improvements Phase II, 1986). The original trapezoidal channel is formed in calcareous clay materials with lenses of calcareous gravels. Channel infilling appears to have occurred following the initial construction of the channel as evidenced by the presence of alluvium over the calcareous clay. The inset channel appears to have developed and downcut through the alluvium and the original calcareous clay bed to form a terrace. The channel bottom has now downcut to the underlying massive limestone bedrock over most of its length. Deposits of coarse gravel and shingles in a coarse sand matrix (0.15 m (o.5 ft) thick) covers the limestone bed in some locations. The flow conveyance of the inset channel, terrace and top-of-bank of the trapezoidal channel were estimated to be 2.0 m^3/s (72 cfs), 8.8 m^3/s (310 cfs) and 36.8 m^3/s (1,300 cfs), respectively. Bankfull flow for the inset channel correspond to a flow recurrence interval of RI<<1.001 year. A similar morphology was observed in the upstream portions of the Creek between Cumberland and Alpine Roads.

The lower reaches of Williamson Creek (drainage area 80 km^2 (30.8 mi^2)), were observed to have an inset channel morphology similar to that observed in East Bouldin Creek. Bed materials range from a soft shale to cobble and boulder armor. Banks are primarily alluvial or comprised of calcareous clay materials. The land use history of Williamson Creek is complex with portions of the watershed still under development. However, the middle third of the basin was developed during the 1950s to 1960s, primarily as single family residential land use. A flood frequency curve for Williamson Creek illustrates the superposition of the minor and major flow regimes and a demonstrable break point in the curve at a Recurrence Interval of RI≈1.5 years (Figure 3.2). The major system curve indicates that basin wide contribution may not occur for flow events with a RI<1.4 years prior to development. Following urbanization the minor system flows occur even under very small rainfall episodes and dominates the flood frequency curve up to RI≈1.5 years. The capacity of the inset channel was determined to range from 1.0 to 2.8 m^3/s (35 to 100 cfs) with a RI<<1.001 years.

The significance of the increase in the minor system flows on channel form following development is illustrated in Fair Oaks Tributary a 0.62 km^2 (0.24 mi^2) tributary to Williamson Creek. Fair Oaks Tributary was developed out by the 1960's as primarily medium density single family homes. A channel with dimensions measuring 5.3 m (17.4 ft) in width and 2.4 m (8 ft) to top-of-bank, was observed in the 1996 survey near Fair Oaks Drive approximately 30 years after buildout of the basin. Bankfull width and depth were estimated to be 3.4 m (11 ft) and 0.8 m (2.6 ft), respectively. Flow at bankfull and top-of-bank were estimated to be 84 with RI<<1.001 years and 480 cfs with an RI≈20 years, respectively. Based on geomorphic evidence, downcutting appears to be in excess of 0.76 m (2.5 ft). The channel has now downcut to bedrock and enlarging through channel widening.

The drainage are of Shoal Creek at its confluence with Town Lake is approximately 33.4 km^2 (12.9 mi^2). The channel is worn into calcareous clay and mudstone materials and the bed is primarily armored with cobbles and boulder sized shingles with exposed bedrock in some locations. The basin was urbanized during the 1940's. Instream works have also been undertaken over much of the length of the channel. In the vicinity of Kingsbury

Street the channel is comprised of a main floodplain, a terrace and an inset active channel. Although erosion of the terrace and active channel are still ongoing, the nest-of-channels morphology appears to be well established. The flow conveyance capacity of the inset channel was estimated correspond to a RI<<1.001 year event.

All of these channel systems have experienced major flood flows over the last 30 years. Two major flows, estimated to be in the order of 20<RI<25 years and RI≈10 years, based on an analysis of USGS data, occurred in 1981 and 1991, respectively. Flow depths exceeded the active and inset channels in both cases. In a catastrophic system, the inset channel morphology would likely have been significantly reworked or washed out. However, geomorphic evidence, including the presence of riparian structures and trees on the terrace and along the active channel riparian zone of greater than 30 to 40 years, suggests that the inset channels are relatively stable in their hydraulic and planimetric form in these watersheds. Consequently, these data indicate that the morphology of the active channel in streams in the City of Austin may be controlled by the minor system flows following urbanization.

Examination of Barton Creek near Barton Hills Access to the Barton Creek Hike & Bike Trail (off 2010 Homedale Drive), indicates that the channel at this point is also characteristic of an in-regime system. The basin tributary to the above section, is primarily non-urban in land use. The channel is formed in massive limestone bedrock with alluvial banks. Trees along the riparian and overbank zones on the east side of the channel were estimated to be in the order of 30 to 40 years old. Trees on the west side of the channel were estimated to be over 50 years in age. The active channel was classified as stable using a Rapid Geomorphic Assessment protocol. The channel through this reach is comprised of exposed bedrock with no appreciable accumulation of bed sediments. A small central channel, which appears to be associated with solutional weathering processes, meanders through the bottom of the active channel. The capacity of the active channel was estimated to be 1,800 cfs which corresponds to a RI<1.5 years (a flow rate of 2600 cfs was determined for the RI=1.5 year at Loop 360 upstream of this station from USGS data).

In conclusion, stream channel morphology within the City of Austin appear to behave in a manner which is consistent with regime theory. The geomorphically dominant events, however, appear to range from 1<RI <5 years for non-urban reaches (this range may increase to 5 <RI <10 years for rock controlled channels formed in massive limestone) to RI<<1.001 years for urban systems. The geomorphic significance of the less frequent flow events in non-urban systems appears to be due to high initial hydrologic losses which effectively eliminate the frequent runoff events. The process of urbanization results in a fundamental shift in the flow regime due to the decrease in hydrologic storativity and the decrease in basin response time. The result is a significant increase in the frequent, or minor system flow events. The increase in flow magnitude and frequency is such that these events become the geomorphically dominate events. The superposition of the minor and major flow regimes produces a complex nest of channels referred to as an inset channel morphology in this discussion.

3.0 IMPERVIOUS COVER COMPUTATION APPROACH

Purpose

Impervious cover information is used for existing and future land use conditions to estimate the anticipated urbanization of a watershed and the corresponding channel enlargement. See Figure 10-1 for the impervious cover/channel enlargement relationships. Also, the impervious cover percentages are input into an USGS regional equation developed for Austin to calculate peak the flow rate for the existing and future 2-year and 10-year storms.

Approach

The University of Texas at Austin will compute the drainage area for each reach and geomorphic survey section and calculate the impervious cover for existing and future conditions at the previously mentioned locations. This work is performed under a contract between the City of Austin and the University of Texas at Austin.

The process of computing the above parameters is managed by providing coordinates for a desired point and inputting this data into an eight directional flow model that calculates the contributing grids (cells) to determine a total drainage area and impervious cover. An average elevation is developed for each 30 meter by 30 meter cell and the model calculates runoff to flow in the direction of steepest slope. The grid system provides watershed drainage area boundaries similar to the City of Austin watershed boundary maps.

Existing and future land use data were provided by the City of Austin. The future land use data is based on geographical units related to the traffic serial zones for employment and population projections. The planning horizon is the year 2040 and the analysis was prepared by the City of Austin Planning Department.

Output

In each watershed assessment, the impervious cover data will be presented with the appropriate reach and geomorphic survey section. The data will appear in several tables including the reach summary and enlargement ratio spreadsheets.

See the following Tables for an example of the impervious cover data format for each watershed erosion assessment report.

TABLE 2-1
EXISTING AND FUTURE IMPERVIOUS COVER DATA*

EROSION ASSESSMENT REACH LAND USES			TOTAL AREA	GIS EX	Future Adjusted
WATERSHED	POINT #	COMMENT	SQ MI	IC (%)	2040 IC (%)
FORT	X-SECT #				
	6806		3.17	43.3	50.5
	6297		3.16	43.4	50.5
	6300		3.12	43.6	50.5
	6302		2.99	44.7	50.3
	6307		2.54	46.3	50.1
	6313		2.15	49.5	50.7
	6608		1.58	53.2	53.2
	POINT #				
	1	U.S. 290	0.25	71.1	76.5
	2	Briarcliff Blvd.	0.48	67.3	70.0
	3	Berkmann Drive	0.61	62.8	65.2
	4	Rogge Lane	0.77	59.2	61.1
	5	u/s of tributary	0.83	58.2	59.9
	6	total tributary	0.45	52.8	52.8
	7	tributary at Wheeless Lane	0.2	55.9	55.9
	8	tributary at Patton Lane	0.09	75.3	75.3
	9	Manor Road	1.42	54.7	54.7
	10	51st Street	1.48	54.2	54.5
	11	Pecan Springs Drive	1.56	53.4	53.4
	12	u/s of tributary	1.61	52.9	52.9
	13	total tributary	0.47	40.6	45.5
	14	Martin Luther King	2.29	48.4	50.3
	15	Webberville Road	2.48	46.9	50.0
	16	Across from Lott Ave.	2.93	44.9	50.2
	17	Across from Delano Street	3.06	44.3	50.4
	18	confluence w/ Boggy	3.3	43.4	50.7

* Provided by the City of Austin

file:impcover.xls

TABLE 2-1
EXISTING AND FUTURE IMPERVIOUS COVER DATA*

EROSION ASSESSMENT		TOTAL	GIS	Existing Landuse Percentages										Adjusted 2040 Landuse Percentages									
		AREA	EX										Adjusted										
WATERSHED	POINT #	SQ MI	IC (%)	SF	MF	COM	OFF	IND	CIVIC	PARK	TRANS	UND	2040 IC	SF	MF	COM	OFF	IND	CIVIC	PARK	TRANS	UND	TOTAL
FORT	X-SECT #																						
	6806	3.17	**43.3**	57.5	4.3	4.6	2.8	0.2	5.9	1.4	2.2	21.1	**50.5**	60.7	5.0	5.6	2.5	3.8	7.5	4.5	9.4	0.9	99.9
	6297	3.16	**43.4**	57.7	4.3	4.7	2.8	0.2	5.9	1.5	2.2	20.8	**50.5**	60.7	5.0	5.7	2.5	3.8	7.5	4.5	9.4	0.9	100.0
	6300	3.12	**43.6**	58.1	4.4	4.7	2.8	0.2	6	1.5	2.1	20.1	**50.5**	60.9	5.1	5.7	2.6	3.6	7.4	4.4	9.4	0.9	100.0
	6302	2.99	**44.7**	59.8	4.5	4.9	3	0.2	6.2	1.5	2.2	17.5	**50.3**	61.4	5.3	5.9	2.7	2.9	7.3	4.3	9.2	0.9	99.9
	6307	2.54	**46.3**	60.7	5.3	5.5	3.5	0.1	5.8	0.5	2.6	16	**50.1**	62.1	6.2	6.7	3.2	1.1	6.6	4.1	9.0	1.0	100.0
	6313	2.15	**49.5**	62.4	6.3	6.6	4.1	0.1	6.4	0	3.1	10.9	**50.7**	61.5	7.3	7.3	3.5	0.3	5.9	4.4	8.7	0.9	99.8
	6608	1.58	**53.2**	61.3	7.8	7.5	5.3	0.1	7.1	0	4.2	6.6	**53.2**	61.3	7.8	7.5	5.3	0.1	7.1	0.0	4.2	6.6	99.9
	POINT #																						0.0
	1	0.25	**71.1**	8.6	26	9.5	20.9	0	14.8	0	5.6	14.8	**76.5**	17.7	23.7	14.9	17.4	0.9	7.6	14.9	1.5	1.3	99.9
	2	0.48	**67.3**	30.1	14	11	17	0	10.5	0	9.3	8.7	**70.0**	35.5	16.1	16.1	11.6	0.7	5.8	12.9	0.8	0.7	100.2
	3	0.61	**62.8**	42	11	9.8	13.7	0	9	0	7.3	6.9	**65.2**	45.8	13.1	13.6	9.5	0.5	5.0	11.1	0.8	0.6	100.0
	4	0.77	**59.2**	51.9	8.9	9.7	10.9	0	7.3	0	5.8	5.5	**61.1**	52.1	11.1	12.1	7.7	0.4	4.7	9.3	2.2	0.4	100.0
	5	0.83	**58.2**	53.9	8.3	9	10.1	0	8.2	0	5.4	5.1	**59.9**	53.5	10.5	11.8	7.2	0.4	4.7	8.6	3.0	0.4	100.1
	6	0.45	**52.8**	66.4	9.3	7.5	0	0.2	8.7	0	4.9	3	**52.8**	66.4	9.3	7.5	0.0	0.2	8.7	0.0	4.9	3.0	100.0
	7	0.2	**55.9**	62.1	7.6	3.9	0	0.5	13.9	0	10.9	1.1	**55.9**	62.1	7.6	3.9	0.0	0.5	13.9	0.0	10.9	1.1	100.0
	8	0.09	**75.3**	17.9	14	8.9	0	1.2	30.9	0	25.2	1.6	**75.3**	17.9	14.2	8.9	0.0	1.2	30.9	0.0	25.2	1.6	99.9
	9	1.42	**54.7**	62.3	7.7	7.8	5.9	0.1	7.5	0	4.7	4	**54.7**	61.2	9.3	9.0	4.3	0.3	5.2	6.0	4.3	0.4	100.0
	10	1.48	**54.2**	62	7.5	8	5.7	0.1	7.3	0	4.5	4.9	**54.5**	61.4	9.0	8.8	4.2	0.3	5.3	6.1	4.4	0.5	100.0
	11	1.56	**53.4**	61	7.9	7.6	5.4	0.1	7.2	0	4.3	6.5	**53.4**	61.0	7.9	7.6	5.4	0.1	7.2	0.0	4.3	6.5	100.0
	12	1.61	**52.9**	61.5	7.7	7.4	5.2	0.1	7	0	4.2	7	**52.9**	61.5	7.7	7.4	5.2	0.1	7.0	0.0	4.2	7.0	100.1
	13	0.47	**40.6**	65.1	2.7	4.6	1.1	0.1	5.5	0	0	21	**45.5**	68.2	3.6	5.0	2.3	0.4	8.7	0.8	8.7	2.5	100.2
	14	2.29	**48.4**	61.9	5.9	6.2	3.9	0.1	6.3	0.6	2.9	12.2	**50.3**	61.4	6.9	7.2	3.5	0.4	6.1	4.3	9.2	1.0	100.0
	15	2.48	**46.9**	61.1	5.5	5.7	3.6	0.1	5.9	0.5	2.7	14.9	**50.0**	62.5	6.4	6.9	3.3	0.6	6.5	4.0	8.9	1.0	100.1
	16	2.93	**44.9**	60	4.6	5	3	0.2	6.1	1.6	2.3	17.2	**50.2**	61.6	5.4	6.0	2.7	2.6	7.2	4.2	9.2	0.9	99.8
	17	3.06	**44.3**	59.3	4.4	4.8	2.9	0.2	6.1	1.5	2.2	18.5	**50.4**	61.1	5.2	5.8	2.6	3.3	7.4	4.4	9.3	0.9	100.0
	18	3.3	**43.4**	55.3	4.1	4.5	2.7	1.3	5.7	1.4	2.4	22.7	**50.7**	60.1	4.8	5.5	2.4	4.4	7.7	4.6	9.6	0.9	100.0

* Provided by the City of Austin

file:impcover.xls

4.0 WATERSHED VITAL STATISTICS

Purpose

Basic watershed and stream parameters are listed to assist watershed managers and residents in the planning and coordination of stormwater management activities. The data is presented in such a manner so in a quick glance the report reader can identify potential opportunities and obstacles in the implementation of stream restoration projects.

Approach

Data will be gathered from the following sources:

- United States Geologic Survey topographic maps
- Soil Conservation Service Soil Survey of Travis County
- Watershed impervious cover from the University of Texas (City of Austin)
- Historical perspective of development in the Austin area from Bureau of Economic Geology
- Park identification from Mapsco Map book
- Existing and planned drainage projects from the Drainage Utility

and input into a table in each watershed assessment.

Output

An example of the final output in each report is provided from the Williamson Creek Watershed Erosion Assessment.

Williamson Creek Watershed Vital Statistics (Example)

Drainage Area - 19,739 acres = 30.84 square miles (from City of Austin GIS Report, 8/27/96)

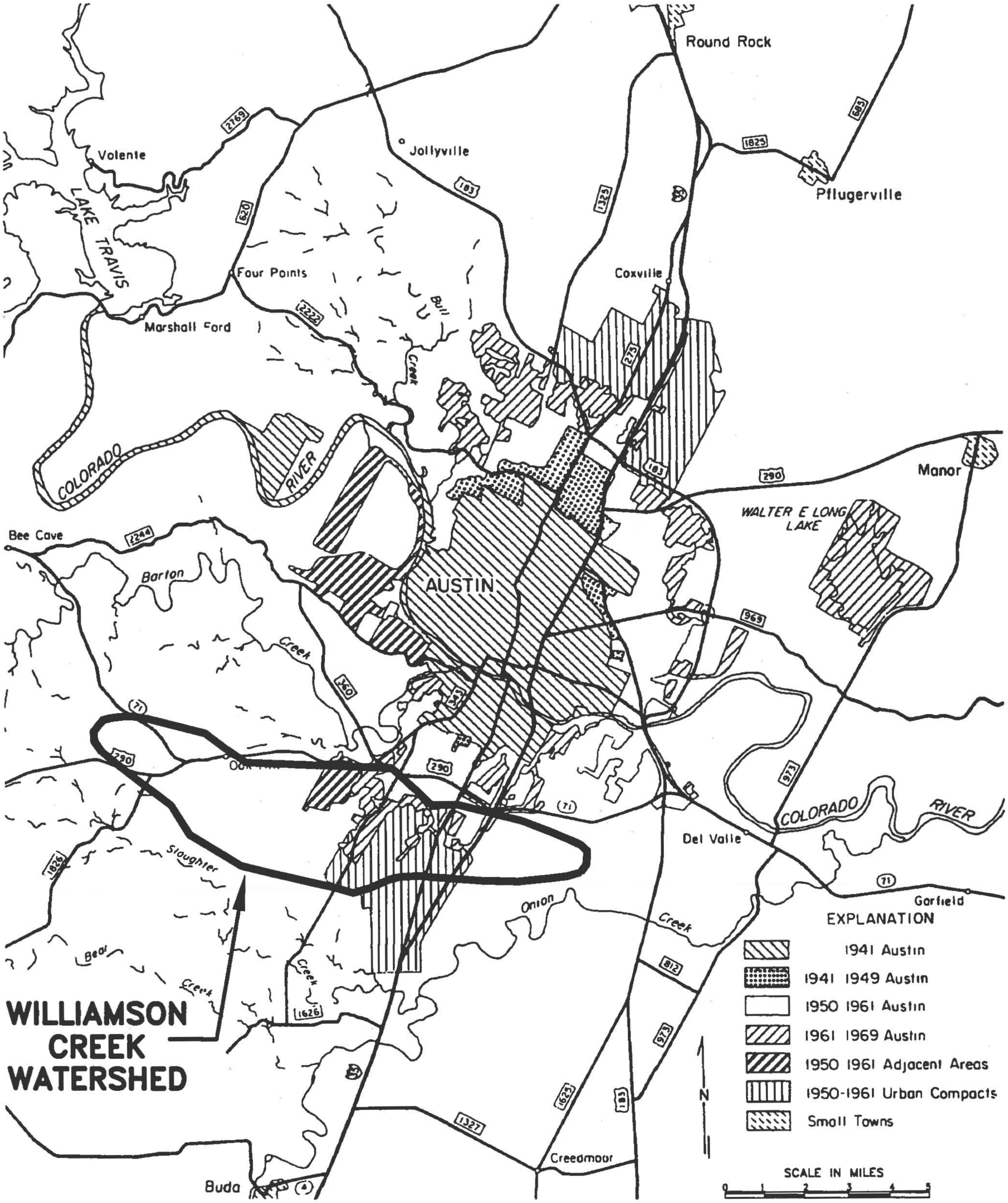
Watershed Impervious Cover

Existing Impervious Cover - 21 percent

Future Impervious Cover (2040?) - 31 percent

Watershed Development Began - 1950's in the middle of the watershed

Watershed Development - The middle third of the watershed is completely developed , with the lower and upper portions of the watershed still developing. See the following Figure for a historical perspective of development within the watershed. Commercial



AREAL GROWTH IN AUSTIN FROM 1941 TO 1969
SOURCE: ENVIRONMENTAL GEOLOGY OF THE AUSTIN AREA, UT–AUSTIN

FIGURE 4–1 **HISTORICAL DEVELOPMENT MAP** WILLIAMSON CREEK WATERSHED EROSION ASSESSMENT CITY OF AUSTIN	*RAYMOND CHAN & ASSOCIATES, INC.* *CONSULTING CIVIL ENGINEERS* *1102 WEST AVENUE* *AUSTIN, TEXAS 78701* *PH. (512) 480–8155 FAX (512) 480–8811*	SHEET 1 OF 2
	JOB NO.: 225	DATE: 09/11/97
	CADD FILE: 225\WILL–FIG1–1	

development is slated for the lower watershed according to the Austin Plan and mostly single family development is probable for the upper watershed. The Edwards Aquifer Recharge Zone Ordinances that manage development in the upper portion of the watershed will limit impervious cover and potentially direct most development to be single family in nature. The watershed ordinances require water quality and detention ponds to manage the quality of runoff from frequent events and provide stormwater detention for large rainfall events. Therefore, peak runoff rates from the upper watershed during frequent storm events may be significantly reduced by the above mentioned ponds and buffer zones.

Stream Length - = 17.48 miles from Onion Creek to the headwaters

Elevation Difference - From elevation 1050 at the headwaters to elevation 483 at Onion Creek = 567 feet

Average Creek Bed Slope - 0.6 percent

Major Tributaries - St. Elmo, Pleasant Hill, Sunset Valley, Cherry Creek, Kincheon Branch, Motorola, Scenic Brook

Typical Soils - According to the Travis County Soil Conservation Service (SCS) Soil Survey

Austin Soils and urban land complex - Silty clay soils underlain by fractured chalk.

Brackett Soils and urban land complex- Gravelly clay loam underlain by limestone.

Eddy Soils and urban land- Gravelly loams that developed over chalk.

Houston Black Soils and urban land- Well drain clay soils over chalk and in alluvial areas.

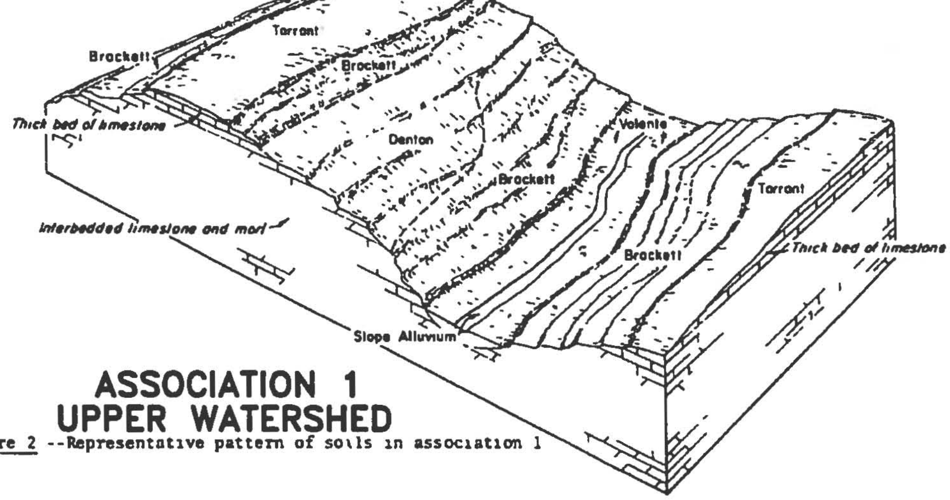
Tarrant Soils and rock outcrop- Stoney, clayey soils overlying limestone.

The soil profile is shown on the following Figure and was obtained from the SCS Soil Survey. Field observations verified the soil profile to be representative of the actual creek conditions.

Parks within the Williamson Creek and tributaries riparian corridor:

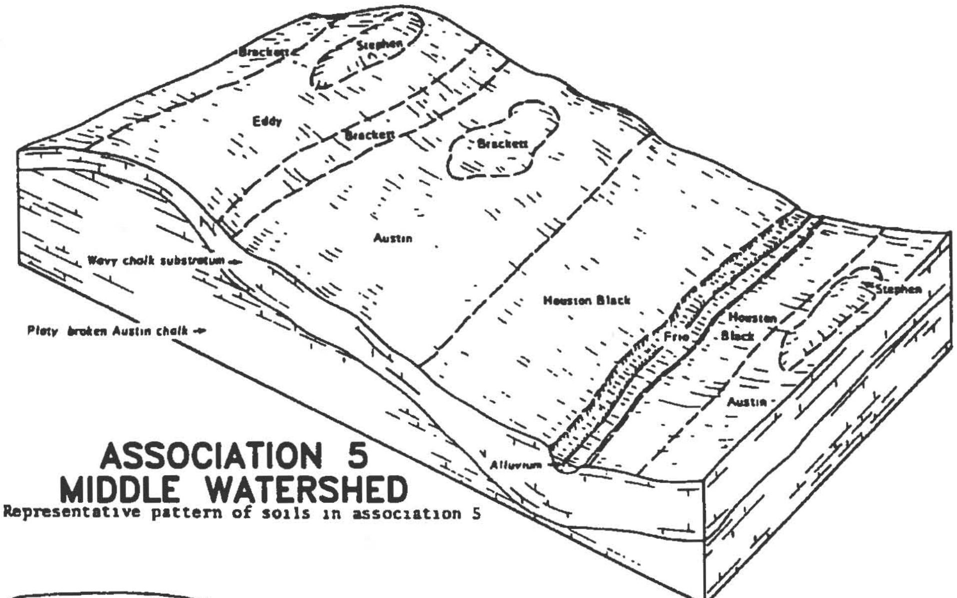
McKinney Falls State Park
Jimmy Clay Golf Course
Williamson Creek Greenbelt
Valley Creek Park in Sunset Valley
Dick Nichols District Park (Kincheon Branch)

Significant Features - The Edwards Aquifer Recharge Zone cuts across the upper half of the watershed from downstream of Brodie Lane to U.S. 290. The watershed soils change dramatically at this point from silts, sands, and clays to rocky creek bottoms and



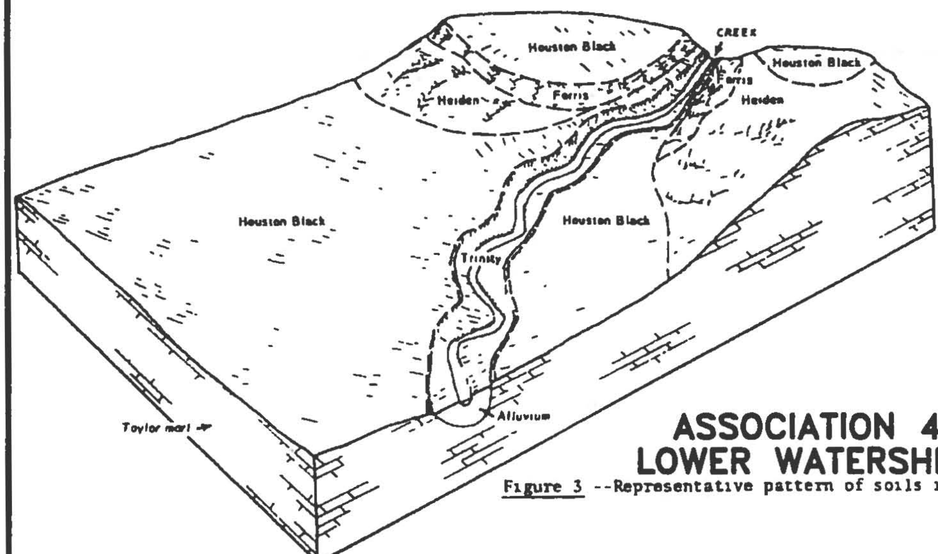
ASSOCIATION 1
UPPER WATERSHED

Figure 2 --Representative pattern of soils in association 1



ASSOCIATION 5
MIDDLE WATERSHED

Representative pattern of soils in association 5



ASSOCIATION 4
LOWER WATERSHED

Figure 3 --Representative pattern of soils in association 4

SOURCE: SCS SOIL SURVEY OF TRAVIS COUNTY

FIGURE 4-2
CREEK SOIL PROFILE

WILLIAMSON CREEK
WATERSHED EROSION ASSESSMENT
CITY OF AUSTIN

RAYMOND CHAN & ASSOCIATES, INC.

CONSULTING CIVIL ENGINEERS
1102 WEST AVENUE
AUSTIN, TEXAS 78701
PH. (512) 480-8155 FAX (512) 480-8811

SHEET 2 OF 2

JOB NO.: 225 | DATE: 09/11/97 | CADD FILE: 225\WILL-FIG1-2 overbanks. The Edwards Aquifer Recharge Zone appears to reduce flow rates below predicted levels during frequent storm events due to the loss of runoff into the porous limestone recharge features.

Past Projects - Numerous wastewater lines cross the creek and run below the channel.

Pleasant Valley Road Bridge and Channel Improvements
Dick Nichols Park Regional Detention Pond
Cherry Creek (Village Branch) Channel Improvements
Numerous on-site detention and water quality ponds

Potential Upcoming Projects - Creek Bend Flood Management Project

Erosion Control Projects at localized areas
Motorola Tributary Regional Detention Pond
Oak Hill Regional Detention Pond
U.S. 290 Channel Improvements in Oak Hill
U.S. 290 Highway Improvements

Williamson Creek Watershed

Watershed Erosion Assessment

N

5000 0 5000

Prepared by Drainage Utility, Watershed Engineering Division
Plotted May 1997

Fort Branch Watershed

Watershed Erosion Assessment

N

2000 0 2000 Feet

Prepared by Drainage Utility, Watershed Engineering Division
Plotted May 1997

5.0 HYDROLOGIC CHANGE AS A RESULT OF URBANIZATION

Purpose

The peak discharge rate for the existing and future 2-year and 10-year storms are calculated for each like reach and geomorphic cross section. The data is used to show the potential for flow increase as a result of new development which provides an indication of the changing flow regime within a watershed. The greater the difference in existing and future peak flow rates the more likely the channel enlargement process is beginning or the stream still has the potential to significantly enlarge. The percent change in peak flow rate can assist in the development of management strategies for each watershed and reach.

Approach

The USGS regional equations developed for the City of Austin in 1986 in the report " The Effects of Urbanization on Floods in the Austin Metropolitan Area, Texas" are input into a spreadsheet to calculate peak flow rates for the existing and future 2- and 10-year storms based on existing and future development conditions. Report excerpts appear following this Section. The USGS equations require drainage area and impervious cover data which is discussed in Section 3.0 of this report. The equations are:

$$\text{2-Year Peak Flow Rate} = 332(CDA)^{0.607}(1+(TIMP)/100)^{1.854}$$

$$\text{10-Year Peak Flow Rate} = 780(CDA)^{0.663}(1+(TIMP)/100)^{1.526}$$

CDA = contributing drainage area, in square miles; and

TIMP = total impervious cover percentage.

The peak flow rate is provided in cubic feet per second.

Output

A summary table will be provided in each watershed report identifying the following parameters:

Reach Number
Reach Location
Drainage Area to reach mid point (square miles)
Existing Impervious Cover Percentage
Existing 2-Year and 10-Year Peak Flow Rates (cfs)
Future Impervious Cover Percentage

Future 2-Year and 10-Year Peak Flow Rates (cfs).

See the attached example table.

TABLE 3-1
HYDROLOGIC SUMMARY

WATERSHED ID	FIRST LEVEL TRIB.	SECOND LEVEL TRIB.	REACH NUMBER	REACH LOCATION	STREAM TYPE	DRAIN. AREA TO APPROX. MIDPOINT (sq. miles)	EXISTING % IMPERVIOUS COVER (%)	EXISTING 2-YR PEAK Q (cfs)	EXISTING 10-YR PEAK Q (cfs)	FUTURE % IMPERVIOUS COVER (%)	FUTURE 2-YR PEAK Q (cfs)	FUTURE 10-YR PEAK Q (cfs)	PERCENT DIFFERENCE 2-YEAR Q (%)	PERCENT DIFFERENCE 10-YEAR Q (%)
	Fort Branch													
FOR	000	000	01	From confluence with Boggy Creek to MKT Railroad.	Alluvial	3.30	43.4	1337	2984	50.7	1466	3219	10	8
FOR	000	000	02	From MKT Railroad to Webberville Rd.	Rock Bed	2.89	45.2	1262	2785	50.4	1347	2939	7	6
FOR	000	000	03	From Webberville Rd. to Springdale Rd.	Alluvial	2.29	48.4	1141	2468	50.3	1169	2516	2	2
FOR	000	000	04	From Springdale Rd. to Manor Rd.	Rock Bed	1.52	53.8	951	1986	54.0	953	1990	0	0
FOR	000	000	05	From Manor Rd. to Tributary at Westminster Dr. and Waterbrook Dr.	Alluvial	1.35	55.5	903	1867	56.1	910	1878	1	1
FOR	000	000	06	From Tributary at Westminster Dr. and Waterbrook Dr. to Rogge Ln.	Structural	0.80	58.7	683	1361	60.5	697	1385	2	2
FOR	000	000	07	From Rogge Ln. to150 ft. D'S Berkman Dr.	Alluvial	0.69	61.0	641	1261	63.2	657	1288	3	2
FOR	000	000	08	From 150 ft. D/S Berkman Dr. to 550 ft. D/S Glencrest Dr.	Structural	0.48	67.3	552	1052	70.0	569	1078	3	2
FOR	000	000	09	From 550 ft. D/S Glencrest Dr. to U.S. 290	Alluvial	0.33	69.2	449	834	73.3	469	866	5	4
				Tributary										
FOR	T01	000	01	From confluence with Fort Branch to Wheless Ln.	Alluvial	0.25	40.6	269	523	44.8	284	547	6	5

6.0 STREAM INVENTORY

Purpose

This aspect of the study was performed to identify existing erosion problems, the stream condition, the stream type (Section 8.0), and potential future watershed problems and opportunities. Numerous photographs will be taken in each watershed to present a pictorial view of the stream to report readers and watershed managers. The photograph log can serve as a benchmark for the stream, allowing future comparisons to be made with the 1997 stream conditions.

Approach

The stream inventory of the entire watershed was performed by hiking the creek and identifying erosion concerns, selecting geomorphic like reaches, measuring geomorphic cross sections, ranking problems per the erosion priority rating, identifying causes of erosion, and listing maintenance needs. The above issues will be noted on the stream inventory forms (Table 6-1) and supplemented by numerous photographs.

It was decided by City personnel that the main branch and tributaries would be investigated up to a contributing drainage area of 640 acres (one square mile). It was determined before the study commenced that all observations would be from left to right looking upstream. The following items were identified during the stream inventory:

6.1 EROSION PRIORITY RATING

Existing erosion problems were noted in the field when the following physical structures were threatened or have the potential for erosion problems in the future:

House or Building located within a potential erosion failure

Parking Lot

Bridge structure or public building

Existing retaining wall (gabions, concrete, rip rap, etc.)

Trees

Utility Poles and utility crossings of the creek

Fences

Steep creek banks within park areas that pose a safety threat

Significant loss of land

When an above feature was identified during the stream investigation, a priority was assigned to each based on the following rating table:

Priority 1 - Primary structure, road, public facility currently threatened and requiring attention in the near future.

Priority 2 – Other resources such as retaining walls, fences, large protected trees and woodlands, currently threatened and areas of substantial land loss due to extreme erosion.

Priority 3 – Resources such as structures, roads, trees, fences not currently threatened but may be threatened by future erosion.

All Priority 1 erosion sites will be investigated by a geotechnical engineer to measure and develop additional data to be input into the City developed erosion prioritization system.

6.2 IDENTIFICATION OF EROSION CAUSES

During the hike of the creek, the condition of the stream banks and bottom were noted periodically and photographs were taken to provide the City with a detailed record of the creek condition. This information can be reviewed in the future to observe the changes in creek bottom width, bank slopes, vegetation, baseflow conditions, channel substrate, and maintenance needs in the watershed. The information would be useful in the development of non point source programs since a baseline condition is now established that can be presented to citizens and politicians to present the changing conditions of Williamson Creek.

An example stream inventory sheet follows and includes the above information, notes of unusual features, and the photograph numbers so a point of interest can be identified in the photograph portion of each report. The photograph number is shown on the maps for the location of the point of interest.

Identification of erosion causes and other following physical features will noted on the stream inventory forms:

- Developing watershed and the creek is evolving to convey increasing stormwater runoff.
  - Widening
  - Downcutting
  - Aggradation
  - Slope failures
  - Plan form change
  - Straightening of channel (increased velocity)
- Wastewater lines in the creek bottom and crossing the creek.
- Wastewater manholes.
- Storm sewer outfalls that generate scour holes downstream of outlets.
- Constructed channels that convey runoff from urbanized areas directly into channel.
- Rock berms from past construction projects that caused scour holes, bank widening and upstream aggradation.
- Severe bends in the creek.

- Erodible soils situated directly above bedrock with no cementing interface.
- Past channelization projects that steepened slopes, increased velocity, and improper termination of the project.
- Culverts without energy dissipation devices.
- In channel disturbances.

6.3 INSET CHANNEL WIDTH AND DEPTH

At periodic points throughout the stream inventory, the field team will obtain an inset channel bankfull width and depth to assist in the preparation of the geomorphic analysis. These bankfull measurements will be obtained in a riffle section and will be based on the indicators of common high water such as exposed roots, moss lines, exposed alluvium, vegetation type, and vegetation condition. The data is noted on the stream inventory form in the appropriate column.

6.4 LIKE REACH DETERMINATION (STREAM TYPE)

One of the primary tasks will be to determine like reaches based on the stream types discussed in Chapter 9.0. The stream will be classified as one of the following four stream types:

- Alluvial channel (AL)
- Rock bed channel (RB)
- Rock controlled channel (RC)
- Structural channel (SC)

The observations from walking the creek allow the close examination of the channel characteristics that can not be determined from aerial photos, topographic maps, and geologic maps. Since the channel conditions have changed dramatically after the development of the geologic and topographic maps in 1977, the field observation is a must in defining the change in stream type. In addition, a significant number of streams have a veneer of alluvial armor over the a channel's rock bed which would cause a map reader to label that stream system as an alluvial channel. Again, the field work allows the accurate determination of the armor layer and the correct labeling of the stream types.

To establish a minimum length for a stream type to qualify as a unique like reach, it was determined that stream type must be at least 20 bankfull widths (approximately 1.2-year storm) in length. A new reach length would also be identified when a tributary of significant drainage area discharged into the main channel. The stream order system from Horton is applied to the studied watersheds. See additional discussion in Section 10.2.

The stream types will be used in the calculation of the enlargement ratio since each stream type will show different responses to urbanization.

6.5 RAPID GEOMORPHIC ASSESSMENT OF EACH LIKE REACH

After the identification of a like reach, the field team will complete a rapid geomorphic assessment form for each like reach to summarize the overall reach condition. Typical conditions throughout the reach will be considered during form completion resulting in the determination of a stable, stressed, or in-adjustment reach. The rapid geomorphic assessment form, shown in Figure 6-1, is based on the presence of channel features shown in each geomorphic process. The score for each process is summed and divided by the total number of processes to compute a stability index for each reach. If the stability index is between 0.0 and 0.2, the reach is in a stable condition. A score between 0.2 and 0.4 indicates a stressed channel condition while a stability index greater than 0.4 reveals a stream undergoing significant adjustment processes. The form can provide a history of the reach since many of the identified features require some number of years to evolve. See Section 9.0 for additional detail on the Rapid Geomorphic Assessment approach.

Output

The field form is presented following this section with an example of the provided data and format. This form is closely linked with the 1"=200 mapping appearing in Section 17.0 and photographs in Section 18.0 to provide additional details.

TABLE 6-1
LIKE REACH SUMMARY

WATERSHED ID	FIRST LEVEL TRIB.	SECOND LEVEL TRIB.	REACH NUMBER	REACH LOCATION	STREAM TYPE	STARTING STATION (FEMA)*	ENDING STATION (FEMA)*	PRIMARY GOEMORPHIC PROBLEM	CURRENT CONDITION	REACH LENGTH (feet)	REACH SLOPE (%)	STABILITY INDEX VALUE	SINUOSITY
	Fort Branch												
FOR	000	000	01	From confluence with Boggy Creek to MKT Railroad.	Alluvial	000000	001100	Aggradation	In Adjustment	600	0.67	0.43	1.09
FOR	000	000	02	From MKT Railroad to Webberville Rd.	Rock Bed	001100	009820	Degradation, Widening	In Adjustment	9,220	0.50	0.44	1.11
FOR	000	000	03	From Webberville Rd. to Springdale Rd.	Alluvial	009820	014800	Widening, Degradation	In Adjustment	4,580	0.83	0.48	1.12
FOR	000	000	04	From Springdale Rd. to Manor Rd.	Rock Bed	014800	019750	Widening, Degradation	In Adjustment	5,560	0.72	0.47	1.00
FOR	000	000	05	From Manor Rd. to Tributary at Westminster Dr. and Waterbrook Dr.	Alluvial	019750	022250	Widening, Degradation	In Adjustment	2,500	0.72	0.49	1.00
FOR	000	000	06	From Tributary at Westminster Dr. and Waterbrook Dr. to Rogge Ln.	Structural	022250	024210	None	Stable	1,750	1.14	0.00	1.00
FOR	000	000	07	From Rogge Ln. to150 ft. D'S Berkman Dr.	Alluvial	024210	025760	Widening, Degradation	In Transition (Stressed)	1,550	1.29	0.30	1.00
FOR	000	000	08	From 150 ft. D/S Berkman Dr. to 550 ft. D/S Glencrest Dr.	Structural	025760	027960	Aggradation	In Transition (Stressed)	2,200	1.00	0.30	1.00
FOR	000	000	09	From 550 ft. D/S Glencrest Dr. to U.S. 290	Alluvial	027960	029310	Widening, Degradation	In Transition (Stressed)	1,350	1.04	0.28	1.00
				Tributary									
FOR	T01	000	01	From confluence with Fort Branch to Wheless Ln.	Alluvial	000000	003850	Widening	In Transition (Stressed)	3,850	0.62	0.25	1.00

*Provided by the City of Austin as Reach Label
Measured length based on 1976 aerial topographic maps and perfromed byRaymond Chan and Associates, Inc.

RAYMOND CHAN AND ASSOCIATES, INC.

FORTBR06.XLS

FORT BRANCH
Stream Inventory

Date: 3/26/1997				Observers:		LSS & MU				Most recent rainfall date: 3/25/97 Amount: 0.41 inches @ Airport
Reach #	Roll #	Photo #	Erosion Rating	Resource (H,R,P,F,T, W,Pipe,RR,PP,WDS,TR)	Channel Type (RC, RB, AL, SC)	Bank Soil Type (L or R,s,gr,co,cl,r)	Bottom Type (s,gr,cl,co,bo,r)	Inset Channel Width (feet)	Approx. Bankfull Depth (feet)	Notes
1	1	1			SC	gab	gab,s,sc			Looking U/S @ mouth of Fort Branch @ confluence Boggy Creek
1					SC					Siltation @ mouth being cleaned out (Flowing water clear)
1	1	2	2	T	AL	cl	s,gr			U/S of gabions 250 feet, erosion left bank 15-20 feet in height; falling trees
1	1	3			AL	cl	s,gr			Photo looking U/S at RR bridge
2	1	4			RB	cl,si	gr, r	21'	0.9'	~200 feet U/S of RR under powerlines, some basal scour
2					RB					Scour channel from drainage right side
2	1	5	2	T	RB	cl	gr, r			30' erosion cut rt. bank 700' U/S of RR bridge, unweathered Taylor exposed
2					RB					Note: Unweathered Taylor (rock) just below alluvium
2	1	6	2	T	RB	cl	r			Slump bank failure, U/S right side, unweathered taylor bottom
2	1	7	2	T	RB	cl	r,gr			Erosion left bank - south/left side of bend, fallen trees, 5-15 feet erosion cut
2	1	8	3	T	RB	cl	r, s, gr			Debris & rock dumping behind house possibly for erosion control
2			3	T	RB	cl	r, s, gr			Erosion outside of bends - Baseflow continues
2	1	9	2	T	RB	cl, AL	r, s, gr			20' Erosion bank right side ~ 200' long, flowing water right trib.
2	1	10	3	H	RB	cl, AL	r, s, gr			Dumping along right bank behind new manufactured home.
2	1	11	3	T	RB	cl, AL	r, s, gr			SSD off Eleanor right bank, large rock rip rap - photo of unweathered taylor & alluvium
2			2	T	RB					Falling and leaning trees
2	1	12	2	T, F	RB	cl, AL	r, s, gr			LOD left bank causing erosion right bank, some SA
2	1	13	3	H, T	RB	cl, AL	r, s, gr			Erosion right bank, large rock rip rap, house 20' TOB
2			3	T	RB	AL, s	r, gr			Some dumping along banks behind Eleanor street, also fallen trees
2	1	14	3	T, SD	RB	AL, cl	r, gr			SSD, SH left bank, LOD, erosion left bank, erosion right upper bank
2			2	T	RB	AL, cl	r, gr			Erosion both banks, falling trees, LOD adjacent to Fort Branch Boulevard, (L1)

Rating Key (Cross Section Surveys will be done at all Type 1 rated sites)
3 = resources not currently threatened, but may be threatened in the future
2 = erosion problem, fence/tree/retaining wall undermined, substantial loss of yard
1 = erosion problem, primary structure and/or roadway threatened
Resource: H=House/Bld, R=Road, P=Parking lot, F=Fence, T=Tree, W=Wall, Pipe=Pipeline, RR=Railroad, PP=Power Pole, WDS=Woods, TR=Hike & Bike Trail
Soils: s=sand, gr=gravel, si=silt, cl=clay, r=bedrock, co=cobble, bo=boulder
Channel Type: RC=rock channel, RB=rockbed, AL=alluvial, SC=structural channel

Fort Br
Reach 1
AL

Table 5. Rapid Geomorphic Assessment Approach For Application To Response Segements

FORM/ PROCESS	GEOMORPHIC INDICATOR	PRESENT: No	PRESENT: Yes	INDEX
EVIDENCE OF AGGRADATION (AI)	1. lobate bars	✓		
	2. coarse material in riffles embedded		✓	
	3. siltation of pools		✓	4/7
	4. medial bars	✓		
	5. accretion on point bars		✓	
	6. poor longitudunal sorting of bed materials		✓	
	7. deposition of sediment in the overbank zone	✓		0.57
EVIDENCE OF DEGRADATION (DI)	1. exposed bridge footing(s)		✓	
	2. exposed sanitary sewer/gas pipelines/etc	✓		
	3. elevated storm sewer outfall(s)	—		
	4. undermined gabion baskets/concrete aprons/etc.	—		
	5. scour pools downstream of culverts/stormsewer outlets		✓	4/7
	6. avalanche faces on bar forms	✓		
	7. head cutting due to knick point migration	✓		
	8.terrace cut through older bar material	✓		
	9. suspended armor layer visible in bank		✓	
	10. channel worn into undisturbed overburden		✓	0.57
EVIDENCE OF WIDENING (WI)	1. fallen/leaning trees/fence posts		✓	
	2. occurrence of Large Organic Debris	✓		
	3. exposed roots on trees		✓	3/7
	4. basal scour on inside meander bends		✓	
	5. basal scour on both sides of the channel in riffle sections	✓		
	6. gabion baskets/concrete walls/etc. out flanked	✓		0.43
	7. length of channel with basal scour > 50%	✓		
EVIDENCE OF PLANIMETRIC ADJUSTMENT (PI)	1. formation of chutes	✓		
	2. evolution of single thread channel to multiple	✓		
	3. evolution of pool-riffle to braided form	✓		
	4. cutoff channels	✓		1/7
	5. formation of islands	✓		
	6. thawleg alignment out of phase with meander geometry	✓		
	7. bar forms poorly formed/re-worked/removed		✓	0.14
	STABLILITY INDEX		SI = 0.43	

Adjustment

The stability index (SI) is defined as:

$$SI = (AI + DI + WI + PI)/m$$

where m=4, AI, DI, WI, and PI are the normalized values of the aggradation, degradation, width enlargement and planimetric indices, respectively. The normalized value for each of the four FORM/PROCESS categories is computed as the sum the GEOMORPHIC INDICATORS for which a Yes determination is reported in the PRESENT column divided by n = the number of GEOMORPHIC INDICATORS used for each index. If a GEOMORPHIC INDICATOR is not applicable note n/a opposite this INDICATOR in the PRESENT column and reduce n by 1. For example, if their are no bridges in the reach then GEOMORPHIC INDICATOR No. 1 "exposed bridge footing(s)" under "EVIDENCE OF DEGRADATION (DI)" is not applicable and the observer should record an n/a opposite this INDICATOR, reduce n to 9 and move to the next INDICATOR.

7.0 EROSION CROSS SECTIONS – TYPE 1

Purpose

Cross sections will be obtained at each Type 1 creek erosion area to provide detailed information on erosion problem severity. A geotechnical engineer will accompany the field team to develop an understanding of the structure condition and susceptibility to failure. Forms will be completed and a summary of each erosion site will be provided to present the erosion problem in parameters that can be input into the erosion prioritization system. For location and presentation purposes, each Type 1 erosion site will be identified on the 1"=200 scale mapping and the overall watershed map in each report.

Approach

Relying on the list of Type 1 erosion problems identified during the stream inventory, the field team including the geotechnical engineer will return to obtain a cross section to define the severity, nature, and potential for future problems. The geotechnical investigation will be performed by Jack Holt & Associates, Geotechnical Engineers to provide input on overall slope stability and potential for slope and /or structural failure.

At a Type 1 erosion problem, temporary benchmarks will be established on both banks of the creek to serve as a reference point for cross section measurements. From the temporary benchmarks, horizontal and vertical measurements will be obtained to define the size, and shape of the channel. The data will be tabulated on the forms that appear in this Section. The following data will be tabulated on the forms generated by RC&A:

- Location, Date, Observers, Creek
- Bank angle – measured by a clinometer
- Erodibility Factor – an indicator of the percentage of vegetation on the right and left banks
- Substrate Characteristics – a summary of the bottom material and strength
- Mannings "n" value – a determination of the roughness of the stream in relation to conveyance
- Left Bank soil strata – identify the height, strength, and average soil strata in the left bank
- Right Bank soil strata – identify the height, strength, and types of soil strata in the right bank
- Miscellaneous data to further define the erosion potential
- Cross Section Measurements
- Distance from Structure or Feature to the Top of Stream Bank
- Slope Stability – summarized from the above measurements and observations
- Structure Stability and/or Foundation Integrity – if applicable and summarized from the above.

Bank soil and substrate strength are based upon the type of soil such as a weak strength for sand and silt and a high strength rating for bedrock and limestone. The above information will be used in the prioritization system to assess the erosion threat and compare erosion problems throughout the City.

Output

Forms and notes used in the field to depict the physical conditions at the erosion sites are shown following this section. The data can be used for direct input into the erosion prioritization system to rank and compare erosion problems throughout the City.

Report Presentation

A table will be provided in each watershed report listing the primary parameters identified at each Type 1 erosion site within the watershed. See the following table for an example of the table to be included in each watershed report

TABLE 5-1
TYPE 1 EROSION SITES
PHYSICAL PARAMETERS

FORT BRANCH CREEK SITE LOCATION	AFFECTED ITEM	REACH	STATION ID	VEGATATIVE COVER	ERODIBILITY FACTOR	BANK HEIGHT (ft.)	BANK SLOPE (degrees)	BANK SOILS	SUBSTRATE	EROSION LENGTH (ft.)	DISTANCE TO STRUCTURE (ft.)
100 feet U/S of Robinsdale Lane (extended) at Westminster Drive	Building	5	FOR-MB-021000	< 25%	1	13	50	clay with some sand	calcareous clay with alluvial armor	100	0

FIGURE 5-2
TYPE 1 EROSION SITES
SOLUTION RECOMMENDATIONS*

FORT BRANCH CREEK SITE LOCATION	RESOURCE THREATENED	RECOMMENDATIONS
100 feet U/S of Robinsdale Lane (extended) at Westminster Drive	Shed	Site on outside of meander bend and will continue to erode. Rock boulders or gabions seated below flow line and built up 6 ft. at 2 to 1 slope will allow a shallow slope to be constructed near top of bank. This construction should be extended outside of bend. Total length of construction 100 feet. Must bend gabions on upstream end into sideslope to prevent flanking.

* Assumes site is not part of a reach restoration project

8.0 CHANNEL CLASSIFICATION SYSTEM

Purpose

A like reach is identified to determine the stream type over a segment of channel to be used in estimating the channel enlargement. A channel classification system based on three natural stream types were identified and listed as:

Rock Controlled (RC),
Rock Bed (RB),
Alluvial (AL), with

a fourth type identified as a structural channel (SC). Since stream types respond differently to urbanization, it is very important to select the like reach which is used in developing the channel enlargement, sediment transport, and erosion hazard area.

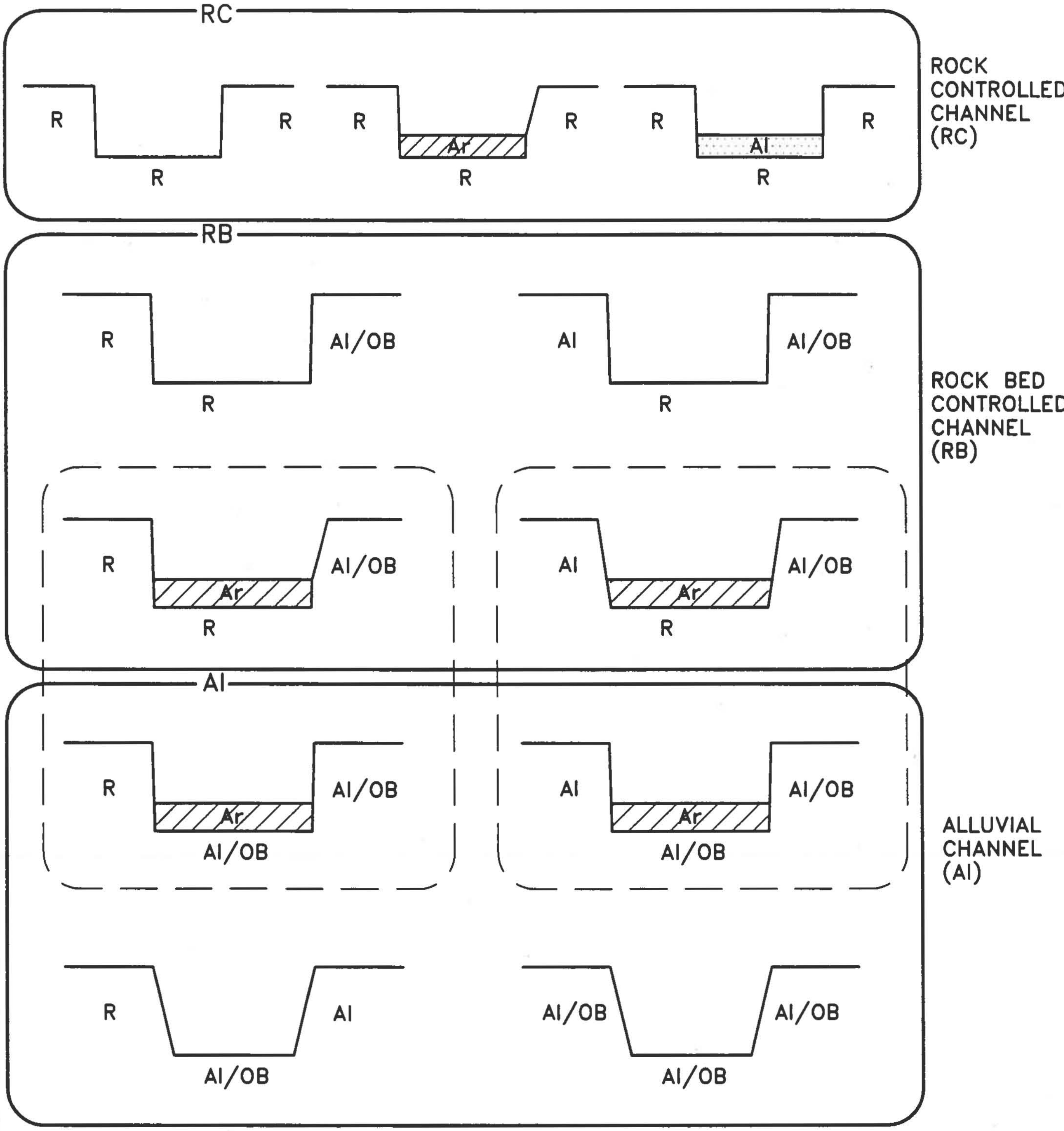
Approach

Prior to the field reconnaissance, the study team reviewed topographic maps, geologic maps, land use data (historic, existing, future) soils maps, and drainage networks to develop a preliminary estimate of the location and length of like reaches. Following the office work, the study team performed a drive-by survey to achieve an understanding of the geomorphology of the channel system and further refine the delineation of like reaches. The field work finalized the like reach locations by pinpointing the alluvial, rock bed, rock controlled, and structural channel stream types. See Figures 8-1, 8-2, 8-3, and 8-4 for schematics of the alluvial, rock bed and rock controlled stream types. This stream classification system is based on a paper developed by A.D. Knighton and is attached.

To further identify the reach condition, the rapid geomorphic assessment form discussed in Section 6.0 will be used to label reaches as being stable, stressed, or in-adjustment. The identification system for cross sections is shown on each stream inventory form which follows this narrative.

Background

Depositional and erosional forms are strongly differentiated according to energy and sediment supply characteristics, which vary in space and time according to autogenic and allogenic mechanisms. The floodplain and the active channel are comprised of a complex composite of these forms. Lewin (1978), generated a suite of floodplain subforms based on three spatial scales:



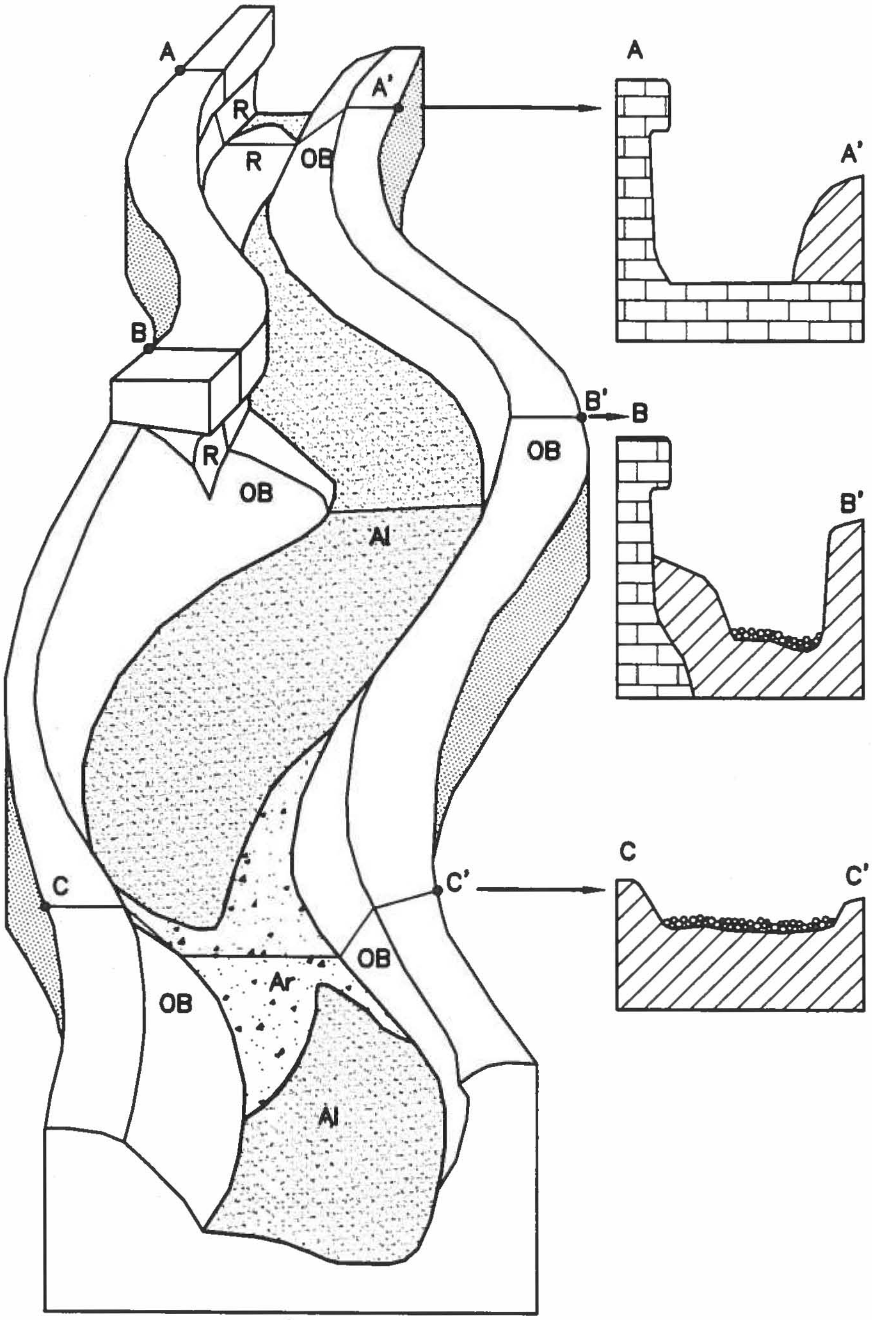
R = ROCK
Al = ALLUVIUM
Ar = ARMOR
OB = UNDISTURBED OVERBURDEN

FIGURE 8-1
CLASSIFICATION OF CHANNEL TYPE BASED ON BOUNDARY MATERIAL AND PROBABLE RESPONSE SCENARIO
WATERSHED EROSION ASSESSMENT
CITY OF AUSTIN

RAYMOND CHAN & ASSOCIATES, INC.
CONSULTING CIVIL ENGINEERS
1102 WEST AVENUE
AUSTIN, TEXAS 78701
PH. (512) 480-8155 FAX (512) 480-8811

SHEET 1 OF 1

JOB NO.: 225 | DATE: 09/09/97 | CADD FILE: 225\chantype-2.dwg



Boundary Material Composition			Aluvial Channel Subclass
Substratum	Substrate	Least Resistant Bank	
R	R	OB	R(R)OB
OB	Al	OB	OB(Al)OB
OB	Or	OB	OB(Ar)OB

ALUVIAL CHANNEL (AL)
TYPE WITH SUBCLASSES

FIGURE 8-2
ALUVIAL CHANNEL (AL) TYPE WITH SUBCLASSES

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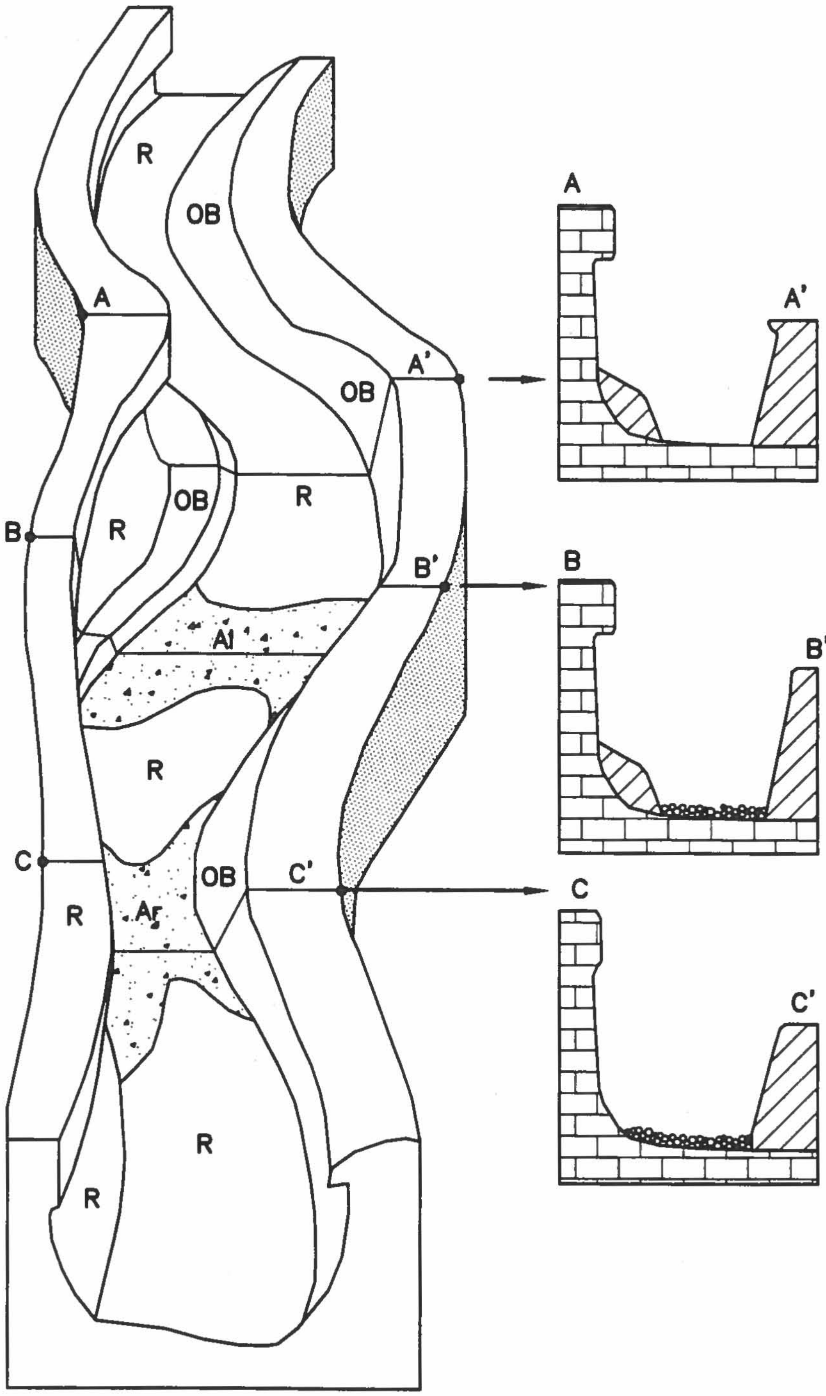
SHEET 1 OF 1

JOB NO.: 225 | DATE: 09/09/97 | CADD FILE: 225\FIGURE\FIG8-2



Boundary Material Composition			Rock Bottom Type Subclass
Substratum	Substrate	Least Resistant Bank	
R	R	OB/Al	
R	Al	OB/Al	
R	Ar	OB/Al	

ROCK BOTTOM (RB) CHANNEL TYPE WITH SUBCLASSES

FIGURE 8-3
ROCK BOTTOM (RB) CHANNEL TYPE WITH SUBCLASSES

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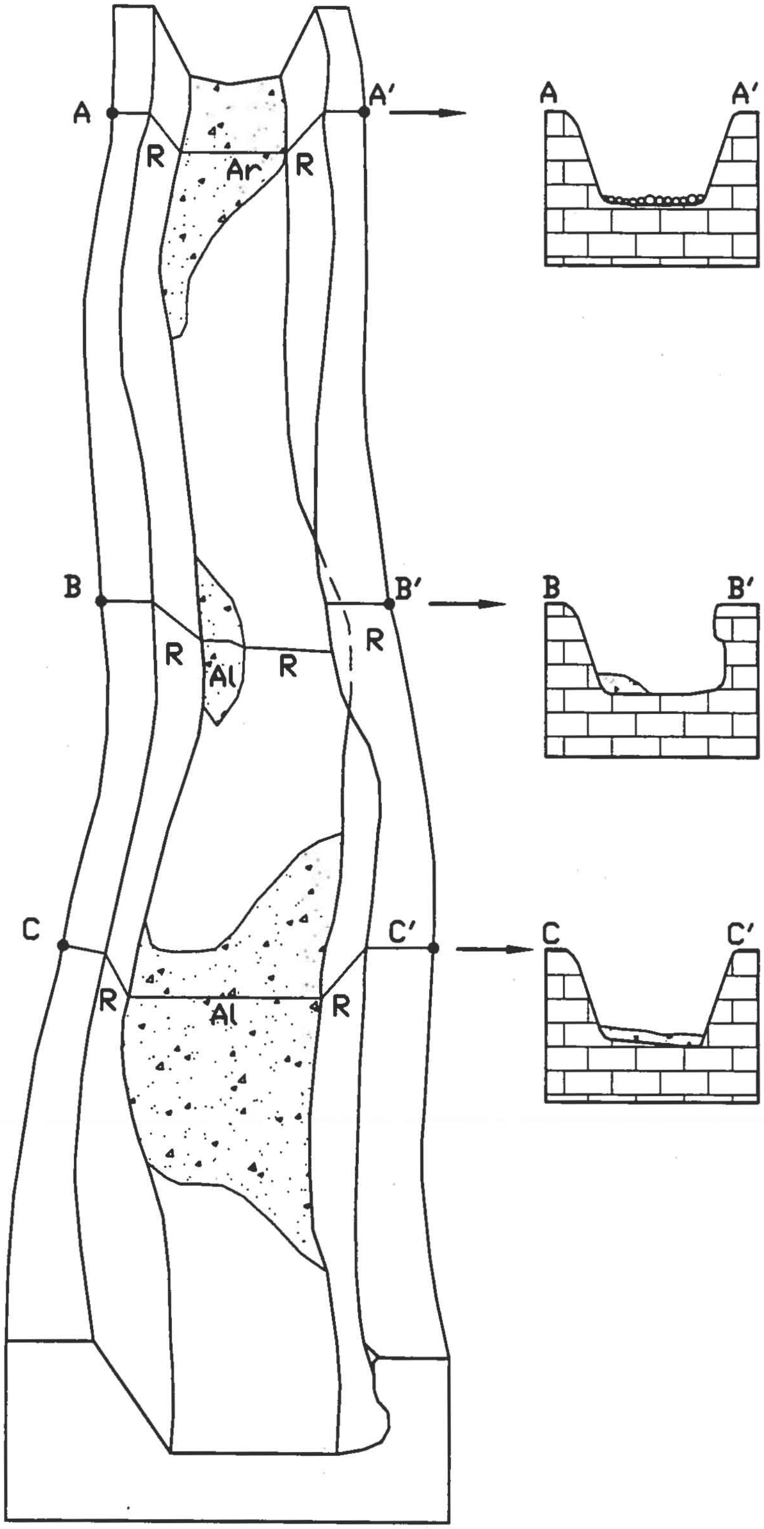
SHEET 1 OF 1

JOB NO.: 225 | DATE: 09/09/97 | CADD FILE: 225\FIGURE\FIG8-3



Boundary Material Composition			RC Type Subclass
Substratum	Substrate	Least Resistant Bank	
R	Ar	R	R(Ar)R
R	R	R	R(R)R
R	Al	R	R(Al)R

ROCK CONTROL (RC)
CHANNEL TYPE &
SUBCLASSES

FIGURE 8–4
ROCK CONTROL (RB) CHANNEL TYPE WITH SUBCLASSES
WATERSHED EROSION ASSESSMENT
CITY OF AUSTIN

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AUSTIN, TEXAS 78701
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JOB NO.: 225 | DATE: 09/09/97 | CADD FILE: 225\FIGURE\FIG8–4

- macroforms, which are of the scale of the floodplain and include the plane form pattern of the floodplain and river channel system;
- mesoforms, which are of the scale of the cross-sectional form of the river channel; and,
- microforms, which are related to perturbations or secondary current patterns in the flow field.

As with any classification system wherein a continuum of associated and overlapping forms are organized into a limited but workable number of sub-groups, difficulties will arise in its detailed application. Problems include:

I. the co-existence of forms in superposition, occurring in response to past and present hydrologic-sediment regimes and having various propensities for preservation through time;
II. complex spatial inter-dependencies. Lewin sights the example: ",..., *an assemblage of point bar swales formed serially in the first place marginal to the main river channel may subsequently form contemporaneous loci for slow overbank deposition of fine sediments, or,..., depending upon the spatial configuration of flood flows, may function as a scouring chute channel during flood flow*"; and,
III. varying time scales of formation and destruction.

The overlap of these forms in space and time result in complex geomorphic features. Local variations in the physical characteristics and rate of supply of sediment, flow hydraulics due to boulders, Large Woody Debris (LWD), knick points, tributary inflows and so on, can further contribute to a wide variance in the dimensions and structure of an observed feature from one observation point to another. The attenuation of flows, sorting of sediments and changes in valley slope and physiography in the downstream direction also leads to significant spatial variations in the form of fluvial features. Despite these variations attempts have been made to classify streams on the assemblage of macro- and mesoforms which comprise the morphology of the channel system (Rosgen, 1996). These morphologically based classification systems have gained wide acceptance in applications on non-urban streams.

In terms of temporal variations, Andrews (1979), Knighton (1987), Frissel et al., (1986) and others have noted the wide variation in relaxation time between micro- to macroscale fluvial features. In a synthesis of relaxation times, Imhof et al., (1996) proposed a hierarchy for geomorphic-habitat elements as described in Table 8.1. A cross-reference with Lewin's (1978) definition of fluvial forms and Andrews' (1979) adjustment scenario shows good agreement between these approaches.

Table 8.1 Hierarchy of Time Scales For Geomorphic-Habitat Elements In Alluvial Channels

System Level	Linear Spatial Scale	Continuous Potential Persistence (years)	Persistence Under Human Disturbance Patterns (years)	Temporal Scale of Fluvial Feature
Watershed	10^5	10^5 to 10^6	10^3 to 10^4	Drainage Network
Sub-Watershed	10^4	10^3 to 10^4	10^1 to 10^2	Macroforms
Reach	10^1 to 10^2	10^1 to 10^2	10^0 to 10^1	Macro & Mesoforms
Site	10^0 to 10^1	10^0	10^{-1} to 10^0	Meso & Microforms
Habitat Element	10^{-1} to 10^0	10^{-1} to 10^0	10^{-2} to 10^{-1}	Microforms

It should be stressed, however, that the rate of geomorphic activity following a disturbance is highly variable from one stream type to another and the adjustment process also tends to be non-linear (see Section 10). Addressing the former cause of variance in mesoforms, alluvial systems in arid regions tend to be more susceptible to a disturbance and possess longer recovery times than channels formed in humid regions (Knighton, 1987). Burkham (1972) reported relaxation times for mesoscale features, as measured by channel width, of 45 to 50 years for the Gila River. In contrast, Hack and Goodlett (1960) noted relaxation times of 10 years for Appalachian streams. Even within alluvial channels within the similar climatic and vegetation zones, variability in the susceptibility of fluvial features to change following a disturbance and the corresponding relaxation times may vary between channels formed in cohesive versus loose, non-cohesive materials (Knighton, 1987). Rates of change and relaxation times for mesoscale features in channel systems worn into resistant rock materials may also be longer than that reported above for alluvial channel systems. Consequently, the above temporal and spatial scales are best used to indicate the probable hierarchy of features and associated alterations.

In addition to the above temporal variations some fluvial systems can be described as oscillatory with a periodicity of several decades in larger drainage basins. Equilibrium concepts do not preclude such systems provide the oscillations result in changes in channel morphology which are within a consensus level of variability (Thorn and Welford, 1994). A pulse behavior related to a large scale episodic event is also common in fluvial systems. For example, a landslide may result in a large influx of sediment to the channel system. This sediment is transported through the channel network as a sediment wave. These sediments may become sorted based on particle size to form a series of waves all of which demonstrate classic dispersion phenomena as they move downstream through the channel network. A series of failures at one site or multiple sites along the length of the channel system may result in the superposition of sediment waves and the production of complex wave forms. Consequently, fluvial systems vary widely through both space and time. Management of these systems, consequently, requires an understanding of the processes and morphologic responses leading to these variances.

Anthropogenic activities in the form of channel straightening, armoring, modification of riparian vegetation, channel constrictions, and so on, together with the alteration in the prevailing sediment-flow regime add to the observed morphological variance. Despite the complexity observed in fluvial forms, however, it became apparent from the inspection of streams within the jurisdiction of the City of Austin that the channel systems respond to an alteration in the driving mechanisms in one of three basic ways:

i) valley formation;
ii) channel widening; and,
iii) channel downcutting.

Further, it was observed that these basic responses could be associated with the boundary material resistance to scour in that: valley formation occurred in channels whose bed and banks were both susceptible to scour; channel widening occurred in channels wherein the banks are highly susceptible to scour relative to the bed; and, channel downcutting was associated with channels whose bed materials were relatively more susceptible to scour than the banks.

These observations have two fundamental implications:

1. Since morphologically based classification systems imply that a relationship exists between form and process and this relationship is disrupted during the adjustment of the channel to alterations in the driving mechanisms associated with urbanization, then a morphologically based classification approach may not be applicable. In addition, these systems appear to have a unique morphology (see Section 2.0) and they do not represent a sub-set of non-urban stream forms. To the authors' knowledge, no equivalent classification system has been developed specifically for urban stream channel systems.

2. Three response patterns may be adequate to describe the behavior of urban streams to an alteration in the driving mechanisms and that these patterns can be represented by grouping stream channels into three broad categories based on boundary material sensitivity to scour after concepts suggested by Knighton (1987). Since the purpose of the geomorphic data base is the collection of data for the development of a riverine management plan, a stream classification system based on probable channel response to an alteration in the driving mechanisms controlling channel form was considered to be desirable.

The three response patterns were consistent with alluvial (AL), rock bed (RB) and rock controlled (RC) channel systems. The response scenarios for each stream type are described in Table 8.2. A graphical summary of the various channel types and sub-types is provided in Figure 8.1 with illustrations of the 3 general channel types and their sub-types being provided in Figures 8.2 to 8.4 for AL, RB and RC channels respectively. A link between mode of adjustment and field estimates of material sensitivity to scour (SCORE)[1], for the various channel types and sub-types is provide in Table 8.3.

Table 8.2 Classification of Stream Type Based on Channel Response Pattern

Channel Type	Channel Response Pattern	Description/Comment
Alluvial or Unconsolidated Overburden (AL; Figure 8.2)	Valley Formation (degradation and widening; ratio of bankfull width to bankfull depth (W_{BFL}:D_{BFL}) tends to increase).	These channel systems are typically formed in alluvium or unconsolidated overburden deposits which are susceptible to scour. Although not accurate in the strict sense of the term, these channels are commonly referred to as alluvial channels.
Rock Bed (RB; Figure 8.3)	The increase in normalized width[2] (W_n), tends to be higher than the increase in normalized depth[3] (D_n). The increase in the ratio of W_{BFL}:D_{BFL}, due to lower degradation, is high	These channels tend to be worn into massive bedrock bed materials or the bed is armored such that the bed materials posses a low rate of weathering associated with mechanical processes. Banks tend to be formed in alluvial or unconsolidated overburden deposits which are relatively susceptible to erosion by scour.
Rock Controlled (RC; Figure 8.4):	Tendency to downcut such that the increase in D_n is greater then the increase in W_n. The ratio of W_{BFL}:D_{BFL} tends to decrease.	These channels are commonly formed in rock materials in which the bed is susceptible to scour as the primary or secondary erosion mechanism in conjunction with either solutional or other mechanical processes (expansion-contraction, spalling, ice plucking, etc.). The banks are relatively resistant and not highly susceptible to mass wasting

A variant of the above general categories are channels formed in thinly bedded, inter-bedded shale-limestone materials which are highly susceptible to mechanical erosion through expansion and contraction process associated with cycles of freezing-thawing

[1] SCORE is defined as the sum of an index of stickiness, plasticity and firmness based on standard soil consistence tests.
[2] The normalized width is the post-development channel width divided by the pre-development channel width at bankfull stage.
[3] The normalized depth is the post-development channel depth divided by the pre-development channel depth at bankfull stage.

and wetting-drying. Scour processes tend to provide a secondary role in removing the weathered veneer and exposing the underlying materials to further weathering. In such cases these channel systems tend to behave in a manner similar to alluvial channel systems.

Table 8.3. Guidelines for the Determination of Mode of Adjustment Based on Susceptibility to Scour (SCORE)

	Mode of Adjustment For Channel Types Formed in Horizontally Bedded Stratified Materials		
Sensitivity To Scour	**Valley Formation**	**Widening**	**Downcutting**
1. $SCORE_{TOE} \approx 0.5(SCORE_{BED})$	AL	RB(Al) or RB(Ar)	RC(Al) or (Ar)
2. $SCORE_{TOE} << 0.5(SCORE_{BED})$	AL(Ar)	RB or RC or AL(Ar)	-
3. $SCORE_{TOE} >> 0.5(SCORE_{BED})$	-	-	RC

1. Bank and bed materials are both susceptible to erosion by scour.
2. Bank materials are much more susceptible to scour.
3. Bank materials are much less susceptible to sour.

The score was developed at each geomorphic survey cross section but was not used on a reach scale process to estimate channel enlargement. Since only one cross section was obtained in this planning level study for a like reach, soil irregularities could not be accurately defined by the score or applied accurately. Rock outcrops were noted during the stream inventory to assist in applying channel enlargement to opposite channel banks.

Report Presentation

The following figure is an example of a table to be included in each watershed erosion report to summarize reach locations, stream type, existing and future development activity and the current reach condition.

TABLE 6-1
LIKE REACH SUMMARY

WATERSHED ID	FIRST LEVEL TRIB.	SECOND LEVEL TRIB.	REACH NUMBER	REACH LOCATION	STREAM TYPE	STARTING STATION (FEMA)*	ENDING STATION (FEMA)*	PRIMARY GOEMORPHIC PROBLEM	CURRENT CONDITION	REACH LENGTH (feet)	REACH SLOPE (%)	STABILITY INDEX VALUE	SINUOSITY
	Fort Branch												
FOR	000	000	01	From confluence with Boggy Creek to MKT Railroad.	Alluvial	000000	001100	Aggradation	In Adjustment	600	0.67	0.43	1.09
FOR	000	000	02	From MKT Railroad to Webberville Rd.	Rock Bed	001100	009820	Degradation, Widening	In Adjustment	9,220	0.50	0.44	1.11
FOR	000	000	03	From Webberville Rd. to Springdale Rd.	Alluvial	009820	014800	Widening, Degradation	In Adjustment	4,580	0.83	0.48	1.12
FOR	000	000	04	From Springdale Rd. to Manor Rd.	Rock Bed	014800	019750	Widening, Degradation	In Adjustment	5,560	0.72	0.47	1.00
FOR	000	000	05	From Manor Rd. to Tributary at Westminster Dr. and Waterbrook Dr.	Alluvial	019750	022250	Widening, Degradation	In Adjustment	2,500	0.72	0.49	1.00
FOR	000	000	06	From Tributary at Westminster Dr. and Waterbrook Dr. to Rogge Ln.	Structural	022250	024210	None	Stable	1,750	1.14	0.00	1.00
FOR	000	000	07	From Rogge Ln. to150 ft. D'S Berkman Dr.	Alluvial	024210	025760	Widening, Degradation	In Transition (Stressed)	1,550	1.29	0.30	1.00
FOR	000	000	08	From 150 ft. D/S Berkman Dr. to 550 ft. D/S Glencrest Dr.	Structural	025760	027960	Aggradation	In Transition (Stressed)	2,200	1.00	0.30	1.00
FOR	000	000	09	From 550 ft. D/S Glencrest Dr. to U.S. 290	Alluvial	027960	029310	Widening, Degradation	In Transition (Stressed)	1,350	1.04	0.28	1.00
				Tributary									
FOR	T01	000	01	From confluence with Fort Branch to Wheless Ln.	Alluvial	000000	003850	Widening	In Transition (Stressed)	3,850	0.62	0.25	1.00

*Provided by the City of Austin as Reach Label
Measured length based on 1976 aerial topographic maps and perfromed byRaymond Chan and Associates, Inc.

RAYMOND CHAN AND ASSOCIATES, INC.

FORTBR06.XLS

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5

River Channel Adjustment - the Downstream Dimension

A. D. Knighton

INTRODUCTION

Natural rivers develop a wide range of network and channel forms, the characteristics of which are a function of position within the fluvial system. Channel geometry at any particular location reflects the influence of upstream controls such as climate, geology, land use and basin physiography, which together determine the hydrologic regime and the quantity and type of sediment supplied. Whether position is defined in topologic, geometric or flow-related terms, the most striking element of fluvial change is in the longitudinal direction, and this chapter focuses on the downstream adjustment of width, depth and slope, components which specify in a broad way two of the three dimensions of the geometry of river channels.

Figure 5.1 presents in summary form the main downstream trends in control and response variables, some of which are less certain than others. Even the most commonly cited elements of longitudinal change - increasing discharge, decreasing bed-material size and decreasing slope - are not universally applicable. One problem in assessing downstream trends stems from the general lack of data at sufficient locations along individual rivers, particularly for sediment-related variables. Consequently in testing theory and in empirical analysis, sequent position along a single river is often replaced by relative position within a group of rivers chosen from a given physiographic area, with the attendant risk of increasing heterogeneity in environmental conditions as the sampled region expands to augment the data base. Bearing this limitation in mind, three related issues are considered here: firstly, the overall *consistency* of downstream adjustment, with emphasis on the main control variables and their relationships to width, depth and slope; secondly, the *adjustability* of those form elements,

First published 1987

Basil Blackwell Ltd
108 Cowley Road, Oxford, OX4 1JF, UK

Basil Blackwell Inc.
432 Park Avenue South, Suite 1503
New York, NY 10016, USA

British Library Cataloguing in Publication Data
River channels: environment and process -
(Institute of British Geographers special publication, ISSN 0073-9006; no. 17).
1. Rivers
I. Richards, Keith, *1949-* II. Institute of British Geographers III. Series
551.48'3 GB1205

ISBN 0-631-14577-X

Library of Congress Cataloging in Publication Data
River channels - environment and process
Includes bibliographies and index.
1. River channels. 2. Rivers. 3. Alluvium
4. Sediment transport. I. Richards, K. S. II. Institute of British Geographers.
GV561.R59 1987 551.48'3 87-5178
ISBN 0-631-14577-X

Phototypeset in 11 on 13 pt Plantin
by Dobbie Typesetting Service, Plymouth
Printed in Great Britain by Page Bros Ltd, Norwich

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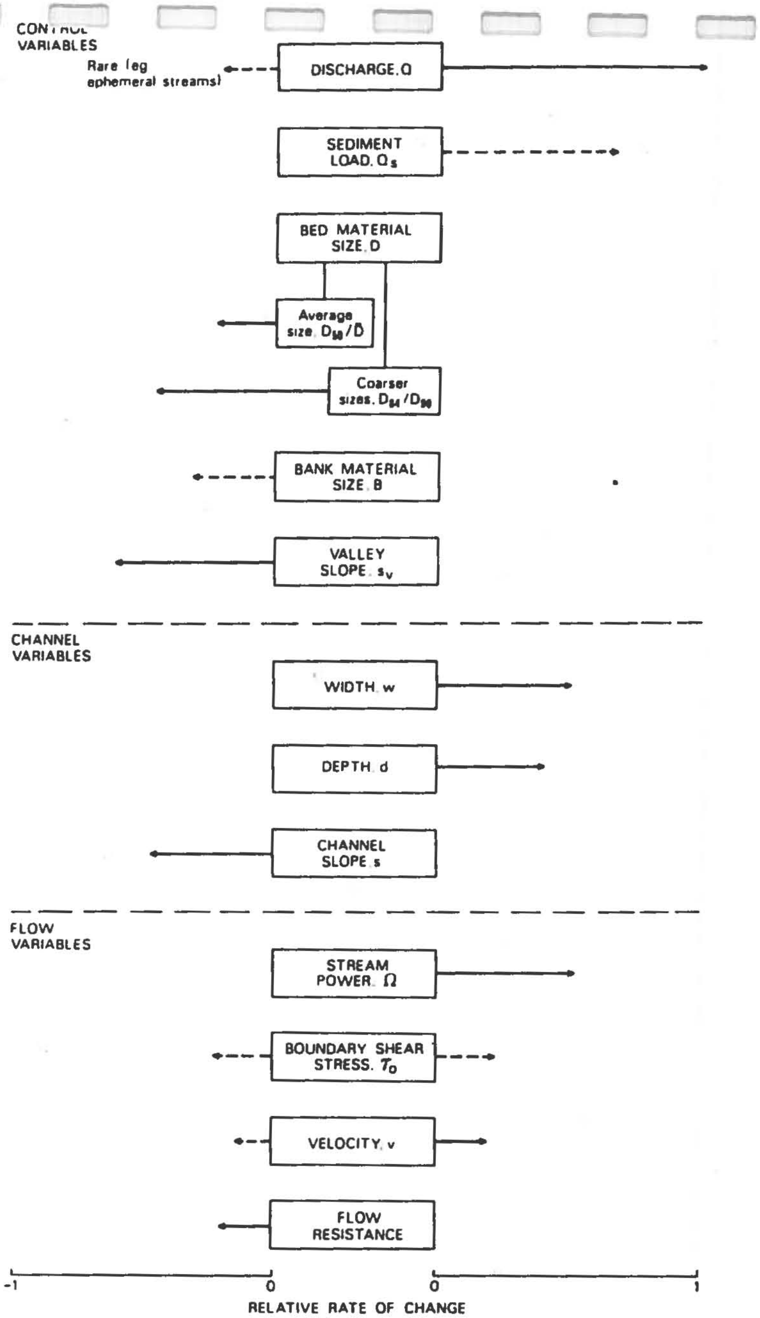


Figure 5.1 Schematic diagram of the relative rates of downstream change. Dashed lines signify greater uncertainty in behaviour

which brings the time factor into account; and thirdly, the *continuity* of adjustment, which focuses more on longitudinal behaviour in single systems and considers the links between networks and channels. All of these issues, but particularly the first two, are related to the question of the ability of a river to develop and maintain an average channel geometry.

DOWNSTREAM CHANGES IN THE CONTROL VARIABLES

The main factors controlling channel form are discharge, sediment load, bed and bank material composition, and valley slope. All can vary considerably along and between rivers. Partly for the practical reason of data availability, discharge has assumed the dominant role in empirical relationships between control and channel-form variables.

Discharge

Downstream change in river discharge is most commonly associated with increasing drainage area. In one of the most comprehensive studies of streamflow variation (Flood Studies Report, 1975), drainage area (A_d) was consistently the dominant catchment characteristic influencing the mean annual flood ($Q_{2.33}$). The overall relationship for the British Isles (table 5.1) was re-analysed on a regional basis and the coefficient a in

$$Q_{2.33} = aA_d^{0.73} \tag{5.1}$$

shown to range between 0.22 and 1.62. Reducing the spatial scale still further and dealing with individual catchments in the Central Region where a = 1.40, sample calculations reveal that coefficient values for the Trent and Tweed basins are 0.57 and 1.78 respectively. Clearly the form of the discharge-area relationship can vary not only between regions but also between basins within the same region, and even within single basins. Nevertheless the relationship serves as a first-order expression for the downstream change in discharge and several results (table 5.1) confirm its general form, with exponent values usually in the range of 0.7 to 0.85. That the exponent is less than unity reflects in part the influence of valley storage on the downstream transmission of higher flows. The way in which flood flows are transmitted can influence channel form, for Burkham (1976) differentiates between low-flow and high-flow systems where the latter are characterized by wider and straighter channels.

As regards channel form adjustment, the quantity of water is less important than its capacity to do erosional and transportational work. Consequently stream

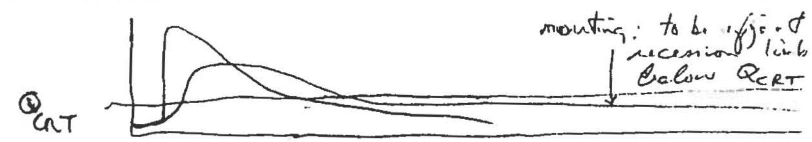


Table 5.1 Discharge-drainage area relations

Source	Location	Drainage area (km^2)	Discharge	a	b
Nixon (1959)	England, 28 stations	111-7276	Q_b	0.24	0.85
Brush (1961)	Pennsylvania	20-162 300	$Q_{2.33}$	0.50	0.80
Benson (1962)	New England, 164 stations	4-25 070	$Q_{2.33}$	0.56	0.85
Nash and Shaw (1966)	Great Britain, 57 stations	8-9900	$Q_{2.33}$	0.76	0.74
Thomas and Benson (1970)	Potomac River Basin	15-30 000	Q_2	0.86	0.80
	Sacramento and San Joaquin River basins	19-4380	Q_2	0.64	0.83
	Louisiana	14-4410	Q_2	4.49	0.56
Emmett (1975)	Upper Salmon River, Idaho	0.4-4670	Q_b	0.42	0.69
Flood Studies Report (1975)	British Isles, 533 stations	0.05-9868	$Q_{2.33}$	0.68	0.77

Discharge (Q) defined as the mean annual flood ($Q_{2.33}$), the flood having a recurrence interval of two years (Q_2), and bankfull (Q_b).
Symbols: $Q = a A_d^b$.

power (γQs), which expresses the rate of doing work per unit length and figures as a parameter in several bed-load transport equations (e.g. Bagnold, 1980), may be more significant than discharge alone but its spatial characteristics at the regional or network scale are poorly understood (Graf, 1983). Nevertheless, the parameter has been used as a basis for theory development (Yang, 1971; 1976; Chang, 1980) and for defining process zones along ephemeral streams (Bull, 1979). Bearing in mind its relationship to bed-load transport, stream power should increase along most perennial rivers at a moderate rate (figure 5.1), with unit stream power remaining approximately constant.

Discharges vary in their effectiveness to transport sediment and modify channel form. Magnitude-frequency analysis suggests that moderate events with return periods in the approximate range of 1.2-3 years transport most sediment (Wolman and Miller, 1960; Pickup and Warner, 1976; Andrews, 1980), one corollary of which being that channel form is adjusted to a similar range of flows. However, the effective or dominant discharge varies with the type of load transported and the hydrologic regime. Thus, as the flow regime becomes more variable because of increasing aridity or decreasing drainage area, more extreme events may have a greater influence on channel form (Baker, 1977; Wolman and Gerson, 1978). Despite the potential longitudinal variation in flow effectiveness, downstream

hydraulic geometry is invariably analysed in terms of a single index of discharge.

Sediment load

Such is the lack of data and intermittency of the transport process that sediment movement patterns at the basin scale are exceedingly difficult to predict. As floodplain width and surface area increase downstream (Bhowmik, 1984), so does the potential for sediment storage. For basins in the southern Piedmont and Wisconsin, Trimble (1975; 1983) has estimated that more than 90 per cent of the sediment eroded from upland slopes since European settlement began is still stored on hillslopes, floodplains and in channels. Thus the sediment delivery ratio which indicates the disparity between supply and transport generally decreases downstream, falling below ten per cent at drainage areas over 100 km^2 (Walling, 1983). Sediment movement patterns are complicated not only by storage but also by the strong contrasts in sediment-streamflow relations both between and within river basins (Andrews, 1980; Meade, 1982).

Sediment transport equations developed for at-a-station conditions translate with unknown efficiency to the downstream case, especially where supply limitations apply. Inasmuch as discharge and stream power increase longitudinally, so should the quantity of sediment load although at a lower rate than that of discharge. Along the upper Salmon River in Idaho (Emmett, 1975), suspended load (in tonnes d^{-1}) increases with bankfull discharge (Q_b in $m^3 s^{-1}$) according to

$$Q_{susp} = 13.1\ Q_b^{0.75} \tag{5.2}$$

Bogardi (1974) gives similar results for Hungarian rivers but emphasizes the importance of local supply conditions and the difficulty of obtaining generalized downstream trends, even for a single river system. Sediment transport rates can vary markedly even over river distances of less than one kilometre (Andrews, 1982).

A particular size fraction moving as bed load at one section may be transported entirely as suspended load at another. Along five New Zealand rivers the ratio of bed load to suspended load declines sharply to approximately ten per cent in lowland reaches (Griffiths, 1983). Even lower values have been recorded elsewhere (Bogardi, 1974; Emmett and Thomas, 1978). Thus the type as well as the quantity of sediment load varies downstream, with bed load transport being possibly dominant only in headwater areas.

Despite the uncertainties surrounding the downstream characteristics of sediment transport, attempts have been made to predict equilibrium channel

Table 5.2 Downstream change in bed material size

Source	Location/River	River distance (km)	Parameter	Bed material range (mm)	Type	β
Yatsu (1955)	Japan: Kinu	0-52	D_{50}	20-70	G	−0.0253
		60-100		0.4-0.9	S	−0.0238
	Watarase	0-21		30-80	G	−0.0531
		23-37		0.3-0.9	S	−0.0416
	Tenryu	14		15-50	G	−0.0532
	Kiso	0-15		35-70	G	−0.0348
		15-55		0.4-0.6	S	−0.0104
	Nagara	0-13		25-40	G	−0.0446
		13-49		0.7-1.2	S	−0.0173
	Sho	0-20		20-50	G	−0.0288
	Abe	0-23		15-90	G	−0.0715
	Yahagi	0-35		1-2	S	−0.0247
Hack (1957)	Virginia, Maryland: Calfpasture	0-27	D_{50}	42-75	G	0.0034
	Tye	0-14		230-680	B/G	−0.0837
	Gillis Falls	0-13		7-45	G	0.115
Bradley et al. (1972)	Knik River, Alaska	0-26	$\bar{D}$	44-330	B/G	−0.081
Rana et al. (1973)	Mississippi, Vicksburg district	440	D_{85}	0.3-0.9	S	−0.0010
			D_{50}	0.2-0.55		−0.00055
			D_{15}	0.18-0.33		−0.00045
Simons and Şentürk (1977)	Rhine	200	D_{50}	50-160	G	−0.011
	Mur	140		34-83	G	−0.0195
	Mississippi, from Fort Jackson	1770		0.12-0.72	S	−0.00085
	Rio Grande, from Otowi	240		0.14-0.50	S	−0.0057
Church and Kellerhals (1978)	Peace	140	D_{90}	45-280	G	−0.0048
			$\bar{D}$	25-120		−0.0034
Knighton (1980)	Bollin-Dean	0-50	$\bar{D}$	0.33-67	G/S	−0.118
	Noe	0-20		29-69	G	−0.042
Nordin et al. (1980)	Amazon, from Iquitos	3300	D_{50}	0.15-0.50	S	slightly negative

Bed material size defined as the median (D_{50}), mean ($\bar{D}$), or that size for which 90 per cent (D_{90}), 85 per cent (D_{85}) or 15 per cent (D_{15}) of the sample is finer.
Symbols: β – rate of change of bed material size downstream in $D = \alpha e^{\beta L}$; B, G, S refer to boulder-bed, gravel-bed and sand-bed streams respectively.

geometry based on transport criteria, in particular the principle of maximum sediment transporting capacity (Kirkby, 1977; White et al., 1981; Ferguson, 1986). As White et al. admit there is no physical justification for such a principle and, given the poverty of the data base, little opportunity for testing it. Nevertheless it is generally agreed that the quantity, type and continuity of sediment transport exert a strong influence on channel form.

Boundary composition

Bed material is derived from slope, tributary and channel boundary sources. Its average size at any location along a river depends on the characteristics of the initial input and on the nature and rate of subsequent modifications to that input, either in place or during transport. With a few exceptions and despite high levels of variability, bed material size generally decreases downstream through the action of such processes as abrasion, weathering and sorting, the rate of decrease tending to be largest in headwater reaches and where gravel sizes dominate the bed (table 5.2). Given this trend a gradual transition from gravel-bed to sand-bed status might be expected along many rivers but the transition, if it exists, is often abrupt once D_{50} approaches 10 mm (Yatsu, 1955; Howard, 1980; Kellerhals, 1982), a discontinuity which has implications for and is related to channel form adjustment (see chapter 4, this volume). In particular particle size and slope are usually strongly related.

Changes in bed material properties also influence the magnitude and type of sediment transport and resistance. Thus, for example, with an idealized downstream sequence of boulder, gravel and sandy beds (see chapter 4, this volume), suspension transport becomes more probable and the dominant type of roughness might alter in the sequence form-grain-form, the first form roughness being associated with the drag exerted by large individual particles (Bathurst, 1978) and the second with the bed forms commonly developed in sand-bed streams. As regards energy degradation by grain roughness, it is reasonable to expect that the larger bed-material sizes (e.g. D_{84}, D_{90}) have a greater effect, and from the limited evidence available (table 5.2) they appear to decrease more rapidly downstream than do average ones.

Whereas an abundant literature exists on downstream changes in bed material properties, the same is not true of bank material despite its acknowledged influence on channel form, especially width. Given relatively uniform supply conditions and a tendency for transported sediment to become finer downstream, channel banks should become more cohesive and have a higher silt-clay content, which is one measure of their erosional resistance. To a certain extent this trend applies to rivers in the mid-west United States (figure 5.2), but it is unlikely to be well defined everywhere and even there, bank material composition is

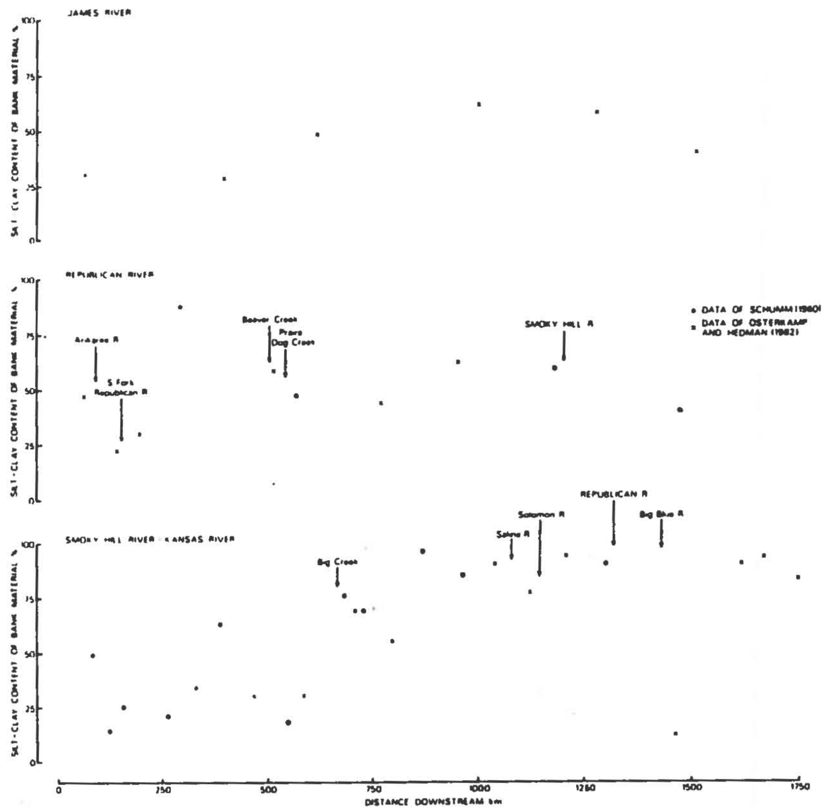


Figure 5.2 Downstream variation in bank silt-clay content along three rivers in the mid-west United States

highly variable. In addition, channel banks are often vertically stratified with a basal gravel layer overlain by fine alluvium (Klimek, 1974; Andrews, 1982; Pizzuto, 1984). In such conditions, bank resistance, and therefore the maintenance of channel width, are strongly related to the strength of the less cohesive basal layer, erosion of which induces block failure in the undercut cohesive material (Thorne and Tovey, 1981).

Regional, longitudinal and local variation exists in the composition of channel boundaries, the level of which is partly dependent on geomorphic history. Nevertheless, one of the more practical classifications of river channels is based on boundary composition (Knighton, 1984), the primary subdivision being into cohesive and non-cohesive channels (table 5.3). Most natural channels are type B, with B1 and B2 dominant. Frequently the bed and banks are composed of

Table 5.3 Channel classification based on boundary composition

Primary type	*Secondary type*	*Characteristics*
A Cohesive	A1 Bedrock channels	No coherent cover of unconsolidated material; generally short reaches
	A2 Silt-clay channels	Boundaries have a high silt-clay content, giving varying degrees of cohesion
B Non-cohesive	B1 Sand-bed channels	'Live-bed' channels composed largely of sandy material (0.063-2 mm) which is transported at a wide range of discharges
	B2 Gravel-bed channels	Channels of gravel (2-64 mm) or cobbles (64-256 mm) which are transported only at higher discharges
	B3 Boulder-bed channels	Composed of very large particles (>256 mm) which are moved infrequently; grades into A1

different material, a common contrast being between cohesive banks and a non-cohesive bed. Given the influence of boundary composition on channel form, empirical results obtained for one type of channel may not apply to another.

Valley slope

This variable is defined as the longitudinal slope of the valley measured along the main valley axis. It is largely an inherited characteristic related to past flow and sediment transport conditions. Despite an overall tendency to decrease longitudinally, the slope of the valley floor can vary significantly as a result of non-alluvial effects such as tectonic activity (Burnett and Schumm, 1983; chapter 2, this volume), or intra-basin contrasts in fluvial history. Thus, below the confluence of the Arkansas and Mississippi rivers, valley slope steepens markedly in response to the relatively high sediment loads carried into the main valley by the Arkansas River during the Pleistocene (Schumm, 1977). Such variations influence the adjustment of channel form, particularly channel slope.

DOWNSTREAM CHANGES IN RIVER CHANNEL FORM

Alluvial rivers with erodible boundaries flow in self-formed channels which, when subject to relatively uniform governing conditions, are expected to show a consistency of form, or average geometry, adjusted to transmit the imposed water and sediment discharges. The problem is to determine the nature of the adjustment process and establish relationships which link control and response variables.

Various approaches have been used to achieve those ends (Ferguson, 1986). *Theoretical* ones fall into two main categories:

1 those which are deterministically based and rely on equations descriptive of the dominant processes, e.g. threshold theory, or Parker's (1978; 1979) model of lateral diffusion, which attempts to resolve the paradox that stable banks are incompatible with a mobile bed;
2 those which postulate additional conditions regarding the behaviour of stable rivers, e.g. minimum variance theory (Langbein, 1964), minimum stream power concepts (Yang, 1976; Chang, 1979), the principle of maximum sediment transporting capacity (White et al., 1981).

While symptomatic of a healthy concern for defining a stable channel geometry, the proliferation of theoretical treatments does underline the fundamental problem of providing sufficient good quality data for effective testing.

Empirical approaches include the regime 'theory' of the Anglo-Indian school of engineers (Lacey, 1930) and its extensions (Blench, 1969), and the hydraulic geometry methodology pioneered by Leopold and Maddock (1953). The two are not strictly equivalent but they become approximately so when downstream hydraulic geometry is applied to rivers with relatively homogeneous conditions of the independent variables.

Relationships have been formulated in a variety of ways, with those based on discharge as the single independent variable dominating analysis. The hydraulic geometry approach expresses the dependent variables, width (w), mean depth (d), mean velocity (v) and slope (s), as simple power functions of discharge-

$$w = aQ^b \tag{5.3}$$
$$d = cQ^f \tag{5.4}$$
$$v = kQ^m \tag{5.5}$$
$$s = gQ^z \tag{5.6}$$

Since not all discharges have the same capacity to perform work, a critical issue is the choice of an appropriate discharge with assumed channel-forming significance. Bankfull discharge is an obvious candidate but it cannot always be defined and is not necessarily of constant frequency (Williams, 1978a). Flows with a specified return period (e.g. the median (Q_2) or mean annual ($Q_{2.33}$) flood) or duration circumvent the latter problem but their accurate definition requires a long period of records. In addition hydraulic geometry relationships refer specifically to the channel only when related to a geomorphic reference level, such as the bankfull state, rather than a particular stage. If discharges with return periods in the range of 1.2-3 years do transport most sediment, then the appropriate choice would seem to lie in that range. Bankfull discharge, which Hey (1978) advocates for design purposes, usually fulfils that condition.

Several extensions of this approach have been proposed; for example, Parker (1978; 1979) introduced dimensionless hydraulic relations based on $w^* = w/D_{50}$, $d^* = d/D_{50}$ and $\tilde{Q} = Q/\{(s_g - 1)gD_{50}^5\}^{1/2}$, arguing that they convey more physical information than their dimensional counterparts. This last point leads naturally to multivariate approaches which include the effects of factors additional to water discharge. However, many of them are not easily quantified. With the paucity of sediment load data, bed and bank material composition have been the main factors involved, largely through the application of multiple regression methods.

Comparison of results is inhibited by the variety of approaches and the use of different discharge indices. Also, many investigations, and particularly those covering a large geographic area, include data from different river types. Distinctions can be drawn between three types of channel:

1 threshold channels in which bed material is entrained only at the highest discharges;
2 channels in which bed material is frequently entrained but transport rates are generally small; and
3 'live-bed' channels where entrainment occurs at discharges well below bankfull and sediment loads are usually high.

Relative to the previous classification (table 5.3), 1 and 2 belong largely to type B2 and 3 to type B1. Maddock (1969) has argued that these different types will not have the same channel characteristics.

Width and depth relationships

Table 5.4 gives the main results obtained at or close to bankfull discharge, grouped according to channel type. Despite the range of conditions covered, the data support the oft-quoted opinion that width varies approximately as the square root of discharge. However, it has been suggested that the rate of change of width is dependent on basin size (Klein, 1981) and climate through its influence on flow regime (Wolman and Gerson, 1978). Wolman and Gerson show that whereas width changes consistently in humid areas, it increases more rapidly in arid ones up to a drainage area of 100 km^2 but remains almost constant thereafter, a distinction not only between perennial and ephemeral streams but also in the relative effectiveness of extreme flows to produce channel widening. However, most of the evidence points to $b \sim 0.5$ where flow is perennially maintained.

The depth exponent (f) has a similar variability to that of b and again there is no clear difference between channel types. Church (1980) suggested the

Table 5.4 Downstream hydraulic geometry relations

Source	Location/Applicable conditions	Discharge	Coefficients a	c	Exponents b	f	z
i Threshold channels							
Kellerhals (1967)	Western Canada (1)	$\sim Q_3$	3.26	(0.42)	0.50	(0.40)	
Li et al. (1976)	Threshold theory	Q_b			0.46	0.46	−0.46
ii Gravel-bed rivers and canals							
Nixon (1959)	Britain (2)	Q_b	3.15		0.49		
Brush (1961)	Appalachians (3)	$Q_{2.33}$	1.85	0.28	0.55	0.36	
Simons and Albertson (1963)	Indian and USA canals, non-cohesive banks (4)	$\sim Q_b$	2.61	0.31	0.50	0.36	−0.24
Emmett (1975)	Upper Salmon River, Idaho (5)	Q_b	2.77	0.27	0.56	0.34	−0.24
Charlton et al. (1978)	Britain (6)	Q_b	3.74	0.31	0.45	0.40	−0.34
Bray (1982)	Alberta (7)	Q_2	4.79	0.26	0.53	0.33	−0.44
*Andrews (1984)	Colorado: thick bank vegetation	Q_b	3.91	0.49	0.48	0.37	−0.41
	thin bank vegetation	Q_b	4.94	0.48	0.48	0.38	−0.41
*Parker (1979)	Theoretical-momentum diffusion	Q_b	4.40	0.25	0.50	0.42	
Chang (1980)	Theoretical-minimum stream power	Q_b			0.47	0.42	
iii Sand-bed rivers and canals							
Lacey (1930)	Canals - Punjab (8)	$\sim Q_b$	4.83	(0.39)	0.50	(0.33)	
Simons and Albertson (1963)	Indian and US canals:						
	sandy banks (9a)	$\sim Q_b$	5.23	0.69	0.50	0.36	−0.30
	cohesive banks, small load (9b)	$\sim Q_b$	3.93	0.58	0.50	0.36	−0.30
	cohesive banks, large load	$\sim Q_b$	2.55	0.45	0.50	0.36	−0.24
Mahmood et al. (1979)	Canals - Pakistan (10)	$\sim Q_b$	4.93	0.53	0.51	0.31	−0.09
iv Undifferentiated							
Rundquist (1975)	Rivers and canals with gravel and sand beds	Q_b	4.39	0.38	0.52	0.32	−0.30
Langbein (1965)	Minimum variance theory	$\sim Q_b$			0.50	0.38	−0.55

Discharge (Q) defined as bankfull (Q_b) or the one with a recurrence interval of 2 (Q_2), 2.33 ($Q_{2.33}$) or 3 (Q_3) years.
Symbols: $w=aQ^b$, $d=cQ^f$, $s=gQ^z$
*Analysis in terms of dimensionless variables. Bracketed coefficient and exponent values come from multivariate relations.

possibility of two regime types, $f=0.33$ and $f=0.40$, associated with relatively large and small sediment transport rates respectively. If they are tentatively equated with sand-bed channels on the one hand and threshold/gravel-bed channels on the other, the data in table 5.4 provide only limited support for the distinction, although extended results for British gravel rivers do appear to conform (Charlton et al., 1978).

Hydraulic geometry exponents are conservative quantities constrained by $b+f+m=1$ and may therefore be rather insensitive. Although also subject to a continuity requirement (a. c. $k=1$), the corresponding coefficient values tend to vary more widely and in so doing reflect more sharply the multivariate character of channel form control. Just a cursory examination of table 5.4 suggests that depths at unit discharge are higher in sand-bed than in gravel-bed rivers.

Discharge, the control whose downstream pattern of variation is best established, acts as a scale variable in determining the gross dimensions of the channel through its largely unknown relationship to the distribution of effective stresses at the channel boundary. That action is constrained by boundary composition. Data from the Missouri basin indicate that, as the bed material changes from a high silt-clay content to sand, there is a systematic increase in the coefficient value (and, to a lesser extent, the exponent) in the width-discharge relation (Osterkamp, 1980). Further increases in bed material size up to a boulder bed reverse the trend. These results suggest that rivers which transport relatively large amounts of sand as bed-material load require a large channel width to maintain sediment movement. Certainly a larger bed load is generally associated with wider, shallower channels, and with respect to gravel-bed streams, Parker (1979) has predicted that a 30 per cent increase in load requires a 40 per cent increase in width. Pickup (1976) has argued that a river adjusts its bed width to optimize bed-load transport, echoing the principle of maximum sediment transport capacity used by White et al. (1981) to predict stable widths and depths. However, sediment load is rarely incorporated in downstream relations and even then only as a derived rather than directly measured quantity (Hey, 1982).

The influence of bed material size on depth is usually contained in multivariate relations, the associated exponent typically lying in the range −0.10 to −0.17 (Lacey, 1930; Kellerhals, 1967; Hey, 1982). Translated into a downstream context, a decreasing bed material size would therefore tend to reinforce the effect of discharge on depth. Comparing Simons and Albertson's (1963) results for gravel and sand-bed canals with non-cohesive banks (4 and 9a in table 5.4, figure 5.3), the latter have width and depth coefficients more than twice those of the former.

Bank material characteristics are an important sedimentological control on the strength and stability of channel banks, and therefore on the adjustment of channel width. Simons and Albertson's (1963) results for sand-bed canals

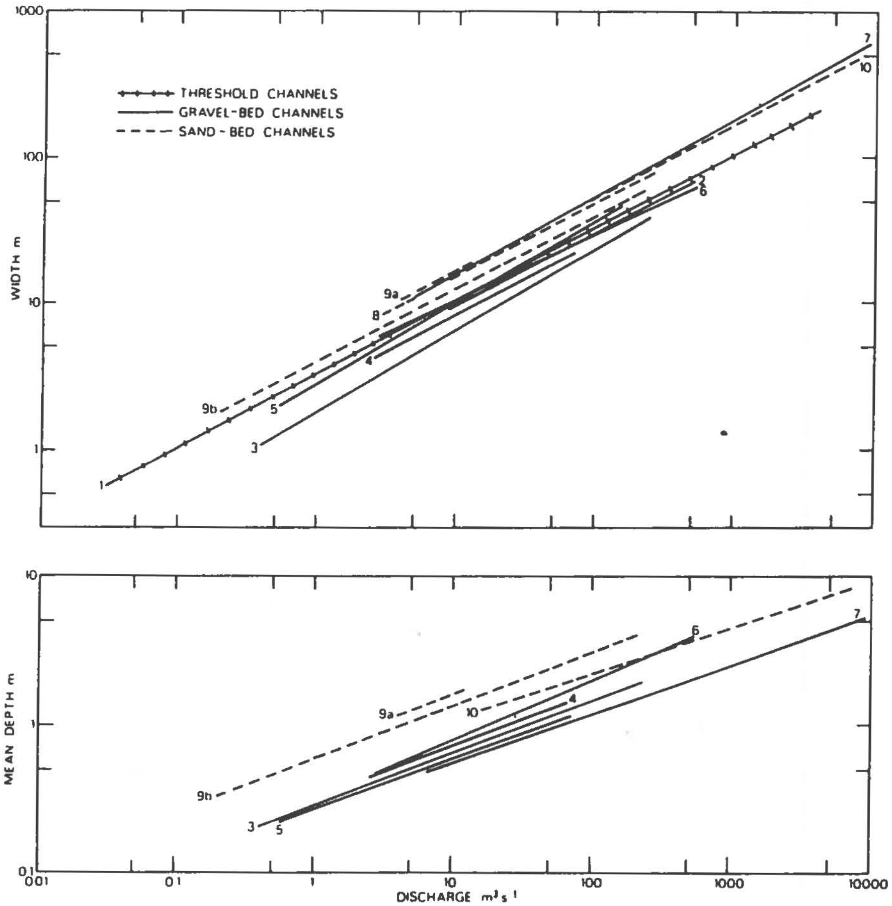


Figure 5.3 Width- and depth-discharge relations plotted over the measured discharge ranges for three types of channel. Numbers refer to table 5.4

illustrate the effect in that the width coefficient for sandy banks is 33 per cent larger than that for cohesive banks (table 5.4, figure 5.3). Although bank strength is not simply correlated with any one material property, it does depend on the degree of cohesion which can be expressed by the silt-clay content of the banks (B) or channel perimeter (M). For sand-bed rivers in the Great Plains, relations have been obtained by Ferguson (1973)

$$w = 33.1\ Q_{2.33}^{0.58}\ B^{-0.66} \tag{5.7}$$

and Schumm (1971)

$$w = 5.54\ Q_{2.33}^{0.58}\ M^{-0.37} \tag{5.8}$$

$$d = 0.12\ Q_{2.33}^{0.42}\ M^{0.35} \tag{5.9}$$

which imply that uniform bank material should give rise to well-defined width- and depth-discharge relations. If banks become more cohesive downstream (B or M increases), which could be associated with an increasing dominance of suspended over bed-load transport, width will increase more slowly and depth more rapidly than expected from the effect of discharge alone.

The resistance of channel banks to erosion is also influenced by the type of vegetation. Charlton et al. (1978) found that channels with grassed banks were on average 30 per cent wider and those with tree-lined banks up to 30 per cent narrower than the overall width-discharge relation would suggest. Results from Colorado (Andrews, 1984; table 5.4) support this conclusion and, in addition, show that the width-discharge relations for British and Colorado gravel-bed rivers are not significantly different, implying some degree of consistency in adjustment within a given class of river.

Bank stability is thus a critical factor in determining channel form. Parker (1978) has formulated a quantitative model for bank stability based on a principle of lateral diffusion. In order to maintain equilibrium in sand-silt rivers, the depletion of material from the banks is countered by the lateral diffusion of suspended sediment which over-loads the flow near the banks and causes deposition, a mechanism for which there is empirical support (Andrews, 1982; Pizzuto, 1984). In gravel rivers the appropriate mechanism is the lateral transfer of downstream momentum which induces a stress distribution allowing a mobile bed but immobile banks at bankfull or dominant discharge. Although not meeting all of the physical requirements of the theoretical model, Colorado gravel-bed rivers have hydraulic characteristics in broad agreement with prediction, particularly as regards the width relation (table 5.4). Those rivers have cohesive banks able to withstand higher stresses than the non-cohesive material considered in Parker's analysis, and in view of this constraint on width, it is perhaps significant that the depth coefficients are about twice that predicted. It is possible that only rivers with sufficient fine sediment to form stable, cohesive banks can approach a fully adjusted channel condition (Osterkamp et al., 1983).

The width and depth of a channel are not adjusted independently. In applying a multiple-equation model to the question of their mutual adjustment, Miller (1984) concludes that whereas discharge has the dominant direct effect on channel development, sediment variables have the dominant indirect effect. Given that the adjustment mechanism integrates indirect effects, Miller maintains that the mutual adjustment of width and depth is primarily dependent on sediment characteristics. To some extent this is borne out by a re-analysis of Schumm's data set (Richards, 1982),

$$w/d = 800\ Q_{2.33}^{0.15}\ B^{-1.20} \tag{5.10}$$

where the sediment variable has the larger influence on the form ratio. Where the ratio is expressed solely as a function of discharge, the coefficient is seen to depend on the type of bank material (Bray, 1982).

Given the multivariate character of channel-form controls, it is perhaps too much to expect consistency in relations where discharge is the only independent variable. However, the effects of factors other than discharge are not easily incorporated, especially in a downstream context, and this applies particularly to sediment transport whose influence can only be assessed in an indirect way. Dimensionless analysis of the kind proposed by Parker (1978; 1979) may produce some improvement by reducing the differences related to absolute scale and allowing any differences due to dynamics to be more clearly seen, but it cannot alter the data problem.

Subdivision of the dimensional relations into the three types, threshold, gravel-bed and sand-bed channels, produces no unequivocal distinctions, except possibly for depth at discharges less than $100\,m^3 s^{-1}$ (figure 5.3). It should be noted, however, that of all the results considered, only Emmett's (1975) apply to a single river system. In addition, many of the plotted relations cover different types of bank material, and as various results have shown, this factor can have a large influence on coefficient values. If downstream change in channel form is capable of determinate solution, the provision of a physically-based width equation which takes account of bank material composition is a primary requirement.

Slope relationships

Whether slope is regarded as a dependent or independent variable depends partly on the time-scale and physiographic setting in which one is working (Schumm, 1977). If slope is treated as part of the dependent downstream geometry, then threshold and regime theory require respectively that either ds or $d^{1/2}s$ is approximately constant along a channel with the same bed material and sediment concentration (Henderson, 1961). Assuming $d \propto Q^{0.4}$, these conditions imply $s \propto Q^{-0.4}$ or $s \propto Q^{-0.2}$ which, given the tenets of the two theories, might apply to coarse material on the one hand and sandy material on the other. This distinction is only partly borne out by the results in table 5.5.

Slope-discharge correlations for natural rivers tend to be rather poor. Coefficient and exponent values have wide ranges and both have been shown to vary with a diverse collection of factors, including physiography (Bray, 1982), bed material characteristics (Osterkamp, 1978) and Froude number (Barr et al., 1980). Such is the scale of variation that it could be argued that any slope-discharge relation is principally a function of the physiographic province in which measurements are made and that no overall tendency exists. Even a good correlation does not necessarily mean that discharge is a major determinant of slope (Prestegaard, 1983). However, downstream changes in discharge influence the ability to transport sediment on which the adjustment of slope ultimately depends. Application of the principle of maximum transport capacity suggests that slope is strongly dependent on sediment transport rate, especially in sand-bed channels (White et al., 1980).

Correlations can be greatly improved by using dimensionless rather than dimensional discharge (Parker, 1982) which, since the dimensionless form contains two parameters, Q and D_{50}, hints at the joint control of discharge and bed material size on channel slope. Bed material size has implications for both particle mobility and channel roughness. In the multivariate relationships of table 5.5 the bed material exponent always exceeds the discharge exponent in absolute value, suggesting that bed material size has the greater effect. Prestegaard's (1983) results for gravel-bed streams confirm that point but Penning-Rowsell and Townshend (1978) found that only at the local rather than reach scale was bed material the more important factor. There is little consistency of coefficient or exponent values in the relationships except possibly for the discharge exponent (~ -0.40) in types (i) and (ii).

The question arises as to the relative significance of different grain-size parameters. For British gravel rivers Charlton et al. (1978) suggested that slope is better related to D_{65} (the threshold grain diameter at bankfull flow) than to D_{90} (the diameter used to represent the size of roughness elements), which emphasizes the transport rather than resistance significance of bed material. To a certain extent the differences between Coloradan channels with thick and thin bank vegetation underline this point in that the relative narrowness of the former, implying a reduced transport capacity, is counteracted by their larger slope (tables 5.4 and 5.5). However, the resistance effect on slope through bed material size has also been emphasized (Leopold and Bull, 1979; Prestegaard, 1983) and in that respect the larger diameters play the dominant role, at least in coarse bed streams. Along the River Hodder Wilcock (1967) found that slope correlated poorly with the median diameter of all bed material but significantly with the median diameter of the 'residual' bed material (defined as that fraction which is immobile at present bankfull flow), implying that slope is more closely related not only to large sizes but also to previous conditions when that material was more mobile.

The downstream rates of change of channel slope and bed material size are closely related, with profiles being more concave where bed material size decreases

Table 5.5 Slope relationships

Source	Location/Applicable conditions	Type of equation: Bivariate	Type of equation: Multivariate
i *Threshold channels*			
Henderson (1961)	Limiting slope for Type B channel		$s = 0.338\ Q_b^{-0.46}\ D_{90}^{1.15}$
Kellerhals (1967)	Western Canada		$s = 0.086\ Q_3^{-0.40}\ D_{90}^{0.92}$
Li et al. (1976)	Threshold theory	$s = g\ Q_b^{-0.46}$	
ii *Gravel-bed rivers and canals*			
Charlton et al. (1978)	Britain		$s = 0.40\ Q_b^{-0.42}\ D_{65}^{1.38}\ D_{90}^{-0.24}$
Bray (1982)	Alberta	$s = 0.0105\ Q_2^{-0.34}$	$s = 0.060\ Q_2^{-0.33}\ D_{50}^{0.59}$
Hey (1982)	Britain		$s = 0.679\ Q_b^{-0.53}\ Q_s^{0.13}\ D_{50}^{0.97}$
Andrews (1984)	Colorado: thick bank vegetation	-	$s = 0.318\ \tilde{Q}_b^{-0.44}\ (\sim 0.587\ Q_b^{-0.44}\ D_{50}^{1.10})$
	thin bank vegetation		$s = 0.162\ \tilde{Q}_b^{-0.41}\ (\sim 0.285\ Q_b^{-0.41}\ D_{50}^{1.02})$
Parker (1979)	Theoretical-momentum diffusion		$s = 0.223\ \tilde{Q}_b^{-0.41}\ (\sim 0.395\ Q_b^{-0.41}\ D_{50}^{1.02})$
iii *Sand-bed rivers and canals*			
Lacey (1930)	Canals - Punjab		$s = 0.211\ Q^{-0.17}\ D_{50}^{0.83}$
Simons and Albertson (1963)	Indian and US canals:		
	sandy banks	$s = 0.00007\ Q^{-0.30}$	
	cohesive banks, small load	$s = 0.0026\ Q^{-0.30}$	
Mahmood et al. (1979)	Canals - Pakistan	$s = 0.0019\ Q^{-0.09}$	
iv *Undifferentiated*			
Rundquist (1975)	Rivers and canals with gravel and sand beds	$s = 0.0032\ Q_b^{-0.30}$	$s = 0.002\ Q_b^{-0.25}\ D_{50}^{0.36}$

Symbols: Discharge (Q, in $m^3\ s^{-1}$): bankfull (Q_b); discharge with a recurrence interval of 2 (Q_2) or 3 (Q_3) years; $\tilde{Q}\ (= Q/[(s_g - 1)gD_{50}^5]^{1/2})$.
Bed material size (D, in m): median (D_{50}); that size at which 65 per cent (D_{65}) or 90 per cent (D_{90}) is finer.
Bed-load discharge (Q_s, in $m^3\ s^{-1}$).

more rapidly (Hack, 1957; Ikeda, 1970). In addition, where a rapid transition from gravel-bed to sand-bed conditions occurs, there can be a distinct break of slope (Yatsu, 1955). Indeed Howard (1980; this volume, chapter 4) draws a sharp distinction between the two types of channel and shows that more rapid decreases in slope occur in the former. Along the River Bollin-Dean, slope decreases markedly as bed material is reduced in size from 64 to 4 mm but changes only slowly once the bed becomes sandy (Knighton, 1975). The variability and possibly the adjustability of channel slope seem to be greater where bed material exceeds about 10 mm in average size.

To maintain a constant bed-load discharge (Q_{sb}) where w and d increase and D decreases downstream, a simplified version of the Einstein-Brown bed-load function

$$Q_{sb} = K\,\frac{w(d.\ s)^3}{D^{1/2}} \tag{5.11}$$

implies that slope must decrease longitudinally at a rate dependent on the rates at which w, d and D change (Knighton, 1984). Based on an assumed equation for shear-stress distribution expressed in terms of the width-depth ratio, Osterkamp *et al.* (1983) demonstrate the co-variation of b, f and z with z normally in the range of -0.25 to -0.40 for $w/d < 50$. These types of analysis emphasize that in addition to or as an alternative to slope, the cross-sectional (and plan) form of a channel can be adjusted to maintain the continuity of sediment transport. The concept of minimum stream power (Chang, 1979) and its equivalent, the principle of maximum transporting capacity (White *et al.*, 1981), imply that for a given discharge a river will minimize its slope in order to attain equilibrium. However, slope minimization is constrained in part by inherited conditions reflected in the gradient of the valley floor. Thus the time-scales of adjustment for the various elements of channel form become relevant.

ADJUSTABILITY OF CHANNEL FORM

Various causes produce change in river channels. Recent floods and man-induced modifications of the fluvial environment are the best documented of those causes but the response they produce may be different in character from that associated with more gradual, secular changes in control conditions, especially as regards temporal lag. Rates of response depend on many factors, including the magnitude and direction of the change, the size and type of channel, and the climatic regime, so that they can be highly variable even within a small area. Consequently representative rates are difficult to define.

Table 5.6 Width adjustment to large floods

River	*Drainage area* (km^2)	*Frequency of event* (years)	*Maximum widening* (%)	*Relaxation time* (years)	*Source*
Patuxent	90	200	64	15	Gupta and Fox (1974)
Baisman Run	4	200	160 (average of 10-20)	1-10	Costa (1974)
Appalachian rivers	0.25-25	100	300-400	10	Hack and Goodlett (1960)
Gila	20 000-25 000	200	600	45-50	Burkham (1972)

Cross-sectional form, at least in the width dimension, appears to be one of the most adjustable components of channel geometry and data for extreme floods indicate relatively short relaxation times (table 5.6). Along the Gila River between 1905 and 1917 (possibly the wettest period since 1650), a series of large winter floods carrying low sediment loads destroyed the floodplain and widened the channel from 90 m to 610 m (Burkham, 1972). From 1918 onwards the floodplain was reconstructed by smaller floods carrying large loads so that by the 1960s the channel had almost regained its former width (figure 5.4a). The ability of a river to recover from such extreme events depends upon the supply of sufficient fine material for channel reconstruction and the rate of vegetative regeneration. Channels in more arid areas where vegetation is sparser tend to have not only longer recovery times but also greater susceptibility to such events. Changes in bed elevation and therefore channel depth over time periods ranging from days to decades can also be produced by large floods, especially in sand-bed rivers. Bed height may increase initially due to the influx of eroded material from upstream and then decrease during a period of degradation when outflow exceeds supply (figure 5.4b).

Rivers adjust their cross-sections in response not only to isolated events but also to more sustained changes having longer-term significance. Downstream of reservoirs where flood peaks and sediment load are much reduced, decreases in bankfull cross-sectional area of over 50 per cent are not uncommon (Petts, 1979). In the Platte River system where peak and mean annual discharges have declined to 10-30 per cent of their pre-dam values, channel widths have been decreased by equivalent amounts over 40-60 years (Williams, 1978b), the narrowing process tending to lag behind the reduction in flow by up to 15 years (figure 5.4c). There also, large fluctuations in depth have accompanied the complex regulation of water and sediment delivery to the rivers. Evidence exists

of change in the opposite direction. Following flow diversion which increased mean annual discharge fifty-fold, the Cheslatta River widened its channel from 5 m to 75-100 m and entrenched itself 10-15 m below the former floodplain within a period of 20 years (Kellerhals et al., 1979). The larger flood flows which typically accompany urbanization can enlarge cross-sectional area by more than six times over periods measured in years rather than decades (Hammer, 1972).

Width and depth can clearly adjust rapidly to altered conditions, the scale and rate of adjustment depending on environmental factors. There will obviously be a time-lag between cause and effect, particularly when control conditions change abruptly. This is especially evident where channel narrowing is the anticipated change, since it requires the import and redistribution of material to form lateral berms and bars. The sensitivity of cross-sectional form raises the question of a river's ability to attain and maintain a stable width and depth, especially where a few large events can produce substantial change. In environments where vegetation and material properties give stability to channel banks, extreme floods appear to have less effect (Costa, 1974; Gupta and Fox, 1974) so that a mean channel geometry can more readily be maintained. Osterkamp et al. (1983) argue that only streams with sufficient suspended sediment approach a fully adjusted condition, and that the flashier the regime the larger the suspended-sediment concentrations need to be if approximate equilibrium is to be achieved.

In regime 'theory' slope is regarded as a dependent variable which can be adjusted when designing a stable channel. Slope adjustment in natural rivers is brought about by aggradation, degradation and changing channel pattern acting singly or in combination. Major floods which supply and redistribute large amounts of sediment can cause large changes in slope at both the reach (Chang, 1982) and profile (Patrick et al., 1982) scales. The Eel River, which in 1964 experienced a flood having a return period greater than 100 years, subsequently degraded its bed in the middle and upper basin and aggraded in downstream reaches to give a significantly modified profile (figure 5.5a). Along a 35 km diversion channel in Manitoba flood flows initiated a period of degradation (up to 4 m) shortly after construction (Kellerhals et al., 1979). Although relatively gentle (0.0005-0.0011), the original design slopes seem to have been the main cause of the problem, being too steep by a factor of almost ten.

Changes to bed elevation and slope can also accompany artificial modifications which disturb the continuity of sediment transport. Channelization both in and downstream of the Tillotoba Creek basin triggered a period of upstream progressive degradation which lowered the stream bed by up to 4.6 m over 20 years (Patrick et al., 1982). The release of sediment-free water below dams tends to entrain material on the bed, resulting in downstream progressive degradation

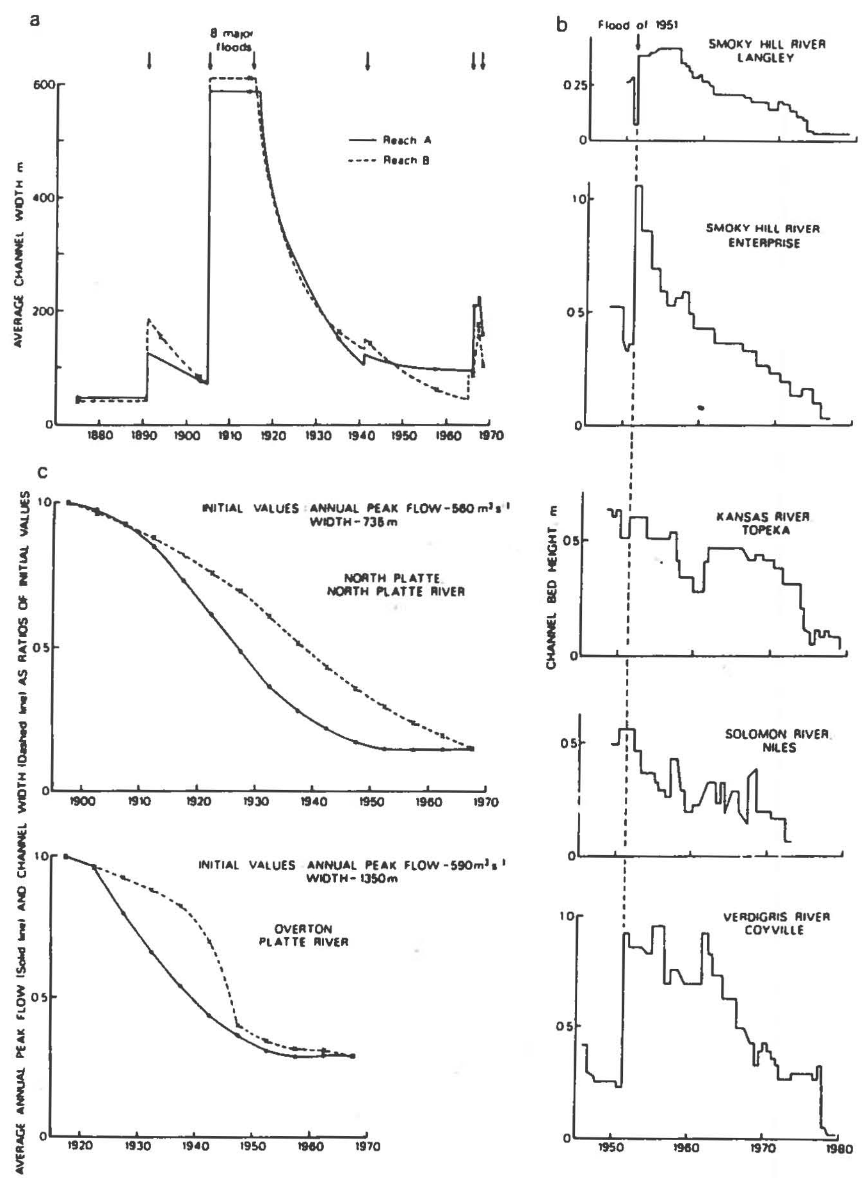


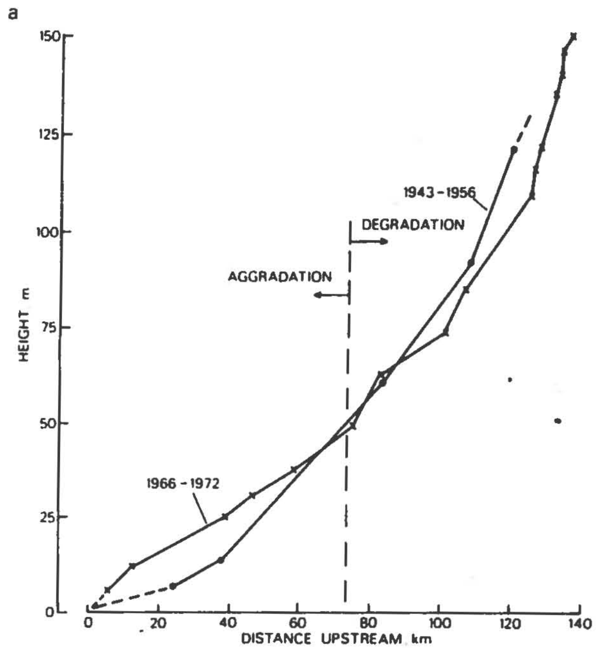
Figure 5.4 Changes in: (a) Channel width, Gila River, Arizona. Arrows indicate major floods (after Burkham, 1972) (b) Channel bed height, Kansas rivers (after Osterkamp and Harrold, 1982) (c) Annual peak discharge and channel width averaged over 5-year periods, Platte and North Platte Rivers, Nebraska (after Williams, 1978b)

and a flatter slope (figure 5.5b). Although initially localized, the effect can be transmitted rapidly over long river distances. Below the Hoover Dam degradation extended 130 km in nine years, reaching a maximum of 7.1 m at a downstream distance of 12.4 km (Galay, 1983).

These and other examples illustrate a potentially rapid rate of slope adjustment where input conditions are substantially modified. However, that adjustment may be constrained by bedrock controls and the effects of bed armouring, notably where degradation is the dominant process for it is slower than aggradation (Gessler, 1971). Also, the attainment of a new stable slope may take many years. In analysing the effects of a flow diversion which trebled mean annual discharge in the Lower Kemano River (Kellerhals et al., 1979), Bettess and White (1983) predict an increase in width and a decrease in slope by a factor of 1.4. Within 20 years width had increased by 1.3 but changes in slope were more modest and they estimate that a complete adjustment of slope could take several hundred years.

This example raises the issue of alternative forms of adjustment. In response to an increased sediment load, the East Fork River has over a period of 40 years changed its depth and roughness without significantly modifying its slope (Andrews, 1979). In Walker Creek, California, which has over 5000 years experienced one episode of infilling and two of incision, the most recent beginning about 100 years ago, gradient adjustments of 2 to 4 per cent have been made but are insignificant when compared with cross-sectional changes (Haible, 1980). Leopold and Bull (1979) conclude from work in semi-arid areas that changes in slope account for only a small part of the adjustment required to achieve a balance between the input and output of sediment load, most of the adjustment being accomplished by changes to other aspects of flow and channel geometry which respond more rapidly.

Because successive channel segments are interdependent, slope adjustment requires the redistribution of very large quantities of material. To that extent alone slope in natural rivers can be regarded either as an imposed parameter, or with valley slope imposed, as a parameter adjustable only over a limited range in the short to medium term. At least part of that limited adjustment can be accommodated by changes to channel pattern, notably sinuosity. Indeed a sinuous river may be better able than a straight one to balance the movement of sediments through the interrelationship of path length, slope and transport capacity (Winkley, 1982). Schumm's (1968) study of the Murrumbidgee River system illustrates that in response to variations in discharge and load over 10^4 years, the required slope adjustments were almost entirely accommodated by changes to channel sinuosity.



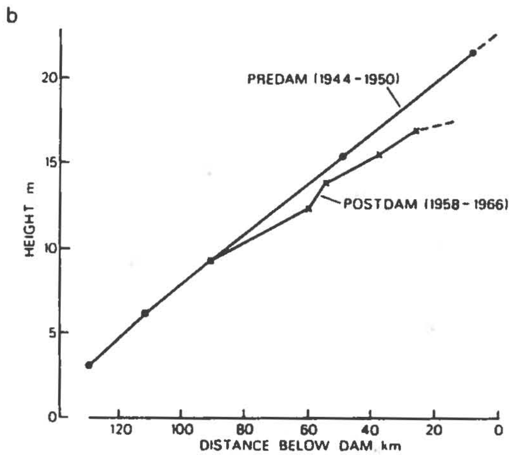


Figure 5.5 Changes in longitudinal profiles
(a) Eel River, California; (b) Downstream of Garrison Dam, Missouri River
(after Patrick et al 1982)

DISCONTINUITIES IN DOWNSTREAM ADJUSTMENT

The equations which describe downstream change in channel form are invariably presented as continuous functions. However, downstream change along individual rivers is discontinuous, principally because of tributary inflow. Other conditions of a random or systematic nature can also produce more or less abrupt transitions in control and response variables, so that orderly change in natural rivers may be limited in spatial extent.

Variations in bedrock structure and lithology create irregularities in fluvial transport and channel form. In the Grand Canyon where the overall channel gradient is dominated by the fall in rapids, channel width is structurally controlled (Howard and Dolan, 1981). In narrower reaches (largely crystalline rocks) transport competence is enhanced and cobble bars are rare, being preferentially deposited in wider sections.

Discontinuities occur in the supply and transport of material, especially where localized mass movements are a major source. A mass of debris containing size fractions which cannot quickly be dispersed will introduce a perturbation into the channel and affect channel gradient in the neighbourhood of the deposit. Repetition of the process downstream could give rise to a stepped river profile in which zones of sedimentation and transport alternate (Church and Jones, 1982). The Bella Coola River in Canada possesses such a sequence. That river seems to have become more stable within the last century, at least in its lower course, possibly because the large volumes of sediment introduced upstream by the erosion of neoglacial moraines are now being exhausted with downstream progression of the sediment wave (Church, 1983). Thus the effects of an initially localized source can be transmitted over long river distances.

Major structural or physiographic boundaries disrupt orderly downstream trends. Uplift along an axis crossing a river causes decreases in slope and depth upstream and the opposite effects downstream, although in the latter the channel may increase in sinuosity to compensate for the steeper valley slope (Burnett and Schumm, 1983; Gregory and Schumm, this volume, chapter 3). In New South Wales where streams descend from an escarpment onto a coastal lowland there is a sharp decrease in width and channel capacity at the transition despite a continuing increase in discharge (Nanson and Young, 1981). Hydraulic relations may be improved if data are stratified according to physiographic criteria (e.g. Bray, 1982).

Of more general significance are the transitions in channel type associated in particular with downstream changes in bed material size. Along gravel-bed sections average grain size tends to decline irregularly until it approaches 10 mm when there is often a sharp transition to a predominantly sandy bed (Yatsu, 1955; Kellerhals, 1982; table 5.2). Such an abrupt decline can produce a discontinuity in profile form and a change in the behaviour of channel slope (Bennett, 1976). Clearly such a transition has implications not only for sediment transport dynamics but also for general stream behaviour. Howard (1980) argues convincingly that gravel- and sand-bed rivers are distinct types with different adjustment characteristics and that downstream transitions should be common. Interestingly Rana et al. (1973) have developed a sediment sorting model which predicts a related grain size-slope transition when bed material is entirely in the sand fraction.

Of all the causes of discontinuity tributary inflow is the most important. Tributary-main stream interaction is a two-way process, but because tributaries are the primary source of discharge addition and major suppliers of sediment, their influence is dominant, inducing both localized and more persistent response. This is evident in the Guanipa basin of Venezuela where a tributary having a lower mean annual but much larger peak discharge causes a ten-fold widening of the main channel below the confluence (Stevens et al., 1975). Major tributaries which carry a lower discharge can nevertheless input a higher load. Relative to the main stream, the Little Snake River in the Yampa basin supplies 27 per cent of the annual runoff but 69 per cent of the sediment load (Andrews, 1980). Aggradation is a frequent response to a large tributary load, especially if the input contains size fractions which the main stream is locally incompetent to transport, requiring gradient and possibly channel pattern adjustments to be made.

Tributaries can alter bed and bank material composition below junctions. The tendency for tributaries to input coarser debris increases average grain size and worsens bed material sorting in the main channel (Knighton, 1980; Troutman, 1980). With a sequence of tributaries, grain size may vary discontinuously in such a way that an exponential decrease below each junction is followed by a stepped increase at the next junction, the magnitude of which could be related to the relative material and channel sizes of the main stream and tributary at each confluence. Occasionally the opposite occurs. Muddy Creek inputs a relatively large load of finer material into the East Fork River, causing a discontinuous change in median grain size from 35–70 mm to 1.25 mm in a distance of 5 km (Andrews, 1979). The Saline and Solomon Rivers introduce large amounts of silt-clay into the Smoky Hill River, increasing *M* sharply (Schumm, 1960). In line with equations (5.8) and (5.9) there is an abrupt increase in channel depth, but despite the large addition of flow, only a small increase in width.

These few examples show that the effects of individual tributaries can be large and highly variable. Consequently they are difficult to incorporate in a general model of downstream channel adjustment. Attempts have been made to relate

hydrological response to network structure (Gupta and Waymire, 1983), and Richards (1980) reasons that channel width can be treated as a link-associated variable with

$$w_\mu = w_1 \mu^k \tag{5.12}$$

where w_μ is the average width of a link having magnitude μ. Thus step changes at junctions are combined with stochastic variation within links. Flint (1974; 1976) has adopted a similar line with respect to link slope (s_μ):

$$s_\mu = s_1 \, (2_\mu - 1)^r \tag{5.13}$$

The sequence of tributary sizes down a main stream is not random because of the spatial requirements of tributary development (Jarvis and Sham, 1981). Equally tributary influence on mainstream behaviour may vary longitudinally with changing relative size. In the upper parts of a basin where the incidence of junctions is high and tributaries of similar size to the main stream are relatively common, frequent adjustments to channel form are probably required (e.g. Rendell and Alexander, 1979). Further downstream only the widely-separated larger tributaries are likely to have a marked effect if relative discharge or magnitude is taken as the criterion for comparison (nevertheless, small steep tributaries can still introduce large sediment loads). In assessing patterns of variation according to stream order, Onesti and Miller (1974) suggest that hydraulic relationships should be better defined with distance downstream as flow and channel variables become increasingly interdependent and natural constraints decline in importance. A network-channel model which accommodates variable tributary influence could provide a basis not only for a more realistic assessment of downstream channel adjustment but also for predicting tributary-mainstream interactions in basins subject to disturbance.

CONCLUSION

Assuming that an average geometry can be defined, the results in table 5.4 suggest

$$w = aQ^{0.5} \qquad d = cQ^{0.36} \tag{5.14}$$

at discharges in the neighbourhood of bankfull, with a ϵ (2.5, 4.8) and c ϵ (0.26, 0.56) as one standard deviation limits for the coefficients. Considering the bias toward humid area rivers, these limits remain quite broad. Some improvement can be effected by using dimensionless variables which include a bed material factor (Parker, 1982) or by stratifying relations according to practical criteria such as physiography or boundary composition but the initial sample needs to be large enough to avoid dangerously small subsets. Classification into three channel types suggests that a, and in particular c, are larger in sand-bed rivers than in the other two types with respective averages of 4.3, 0.56 and 3.2, 0.28 but distinctions are not always sharp (figure 5.3). Although the variability of coefficient, and to a lesser extent exponent values, is increasingly recognized, being dependent at least in part on sediment properties, downstream change in channel form cannot be readily generalized from simple power functions. Multivariate relationships provide only a partial answer because many factors are difficult to quantify. Consistency in downstream adjustment is probably limited to river lengths having relatively orderly change in control conditions and may be better defined in those variables which are more dependent on discharge than sediment characteristics. Thus could the less predictable behaviour of channel slope be explained. In addition, with slope adjustment constrained, width and depth should be better related to prevailing conditions. Definition of an average geometry is even more problematic where the various outputs have different time-scales of response as yet unspecified in an acceptable way.

Given the inherent variability of river systems and the poverty of the data base in key areas, theoretical postulates about downstream behaviour are extremely difficult to test effectively. Different elements of channel form may be determinate to different extents (Mosley, 1981), depending on their relative sensitivity to the quasi-random and discontinuous variations in influential factors which are typical of many natural rivers. Tributaries are the major source of discontinuity and their variable influence both as individuals and in sequence needs to be more formally established within a framework which combines network and channel attributes. Such a development would represent a break from the traditional use of continuous functions and introduce greater flexibility in the assessment of downstream channel adjustment.

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6

Hydraulic and Sedimentary Controls of Channel Pattern

Rob Ferguson

INTRODUCTION

The classic paper by Leopold and Wolman (1957) on 'River channel patterns - braided, meandering, and straight' has had a profound influence on fluvial geomorphology, sedimentology, and engineering. Despite its authors' emphasis that natural channel patterns form a continuum, and are influenced by a great variety of environmental controls, the paper is remembered mainly for its graphical discrimination between braided and meandering channels in terms of just two controlling variables, discharge and slope. This threshold rapidly became part of the conventional wisdom on rivers, spawning similar approaches to other phenomena and a philosophical emphasis on geomorphic thresholds in general (e.g. Schumm, 1979), as well as specific applications to palaeo-environmental reconstruction (e.g. Cheetham, 1980) and the forecasting of channel metamorphosis following human intervention (e.g. Schumm and Beathard, 1976).

Surprisingly few fluvial scientists have paused to ask whether Leopold and Wolman's threshold between meandering and braiding is quantitatively, conceptually, or even morphologically correct. Yet it has been clear for many years that not all rivers have the patterns predicted by Leopold and Wolman's diagram, while some combine elements of both meandering and braiding; that changes in channel pattern downstream or over time are often gradual transitions rather than abrupt crossings of a threshold; and that downstream transitions sometimes occur without major changes in discharge or slope. A common factor in many of these anomalies is variation in type or size of bed material, type of bank material and vegetation, or type and amount of sediment load supplied from upstream. The various roles of sediment as controls of channel pattern

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9.0 GEOMORPHIC SURVEY APPROACH

In Section 8.0 three general channel types were identified (alluvial, rock bed and rock control) based on the probable response scenarios associated with each of these classifications. **The purpose of the geomorphic data base** is to characterize, for each of these channel types, the :

- current state of stability of the channel system;
- the sensitivity of the morphology of the channel to a disturbance in the driving mechanisms controlling channel form; and,
- how the morphology of the fluvial system will evolve should such a disturbance occur.

The design of the geomorphic survey protocol is fashioned around these objectives using a representative sampling of mesoforms in 'like' reaches. The rationale and design of the data collection program is described in the following Sub-Sections.

9.1 MESOSCALE FEATURES

In response to a disturbance in the driving mechanisms, Andrews (1979), noted the following three phase adjustment scenario:

i) initial phase – roughness and depth adjust rapidly to a change in the independent variables (these features may be classified as microforms wherein relaxation times are $t_R > 10^0$ years);
ii) second phase – after a number of years the channel modifies its width until width, depth and roughness are mutually adjusted (these features are considered to be mesoforms which relaxation periods of $10^1 \leq t_R \leq 10^2$ years); and,
iii) third phase – longitudinal channel slope adjusts over an extended period measured in centuries (this parameter is classified as a macroform feature with a relaxation time of $10^2 \leq t_R \leq 10^3$ years) before slope, width, depth and roughness are back into mutual agreement.

In addition to the adjustment of roughness and flow depth, during the initial phase of the adjustment process as described by Andrews (1979), thalweg re-alignment may also occur (MacRae, 1991). This re-alignment represents a slope adjustment for smaller, more frequent flow events and it may be differentiated from planimetric slope adjustment which pertains to meander from change (e.g. meander amplitude, wavelength and radius of curvature) for the active channel. Normally the thalweg and meander geometry are synchronized such that the thalweg travels across the channel bed from the apex of the outside meander bend to the apex of the next meander bend with a cross-over point in the riffle element between meander bends. The re-alignment of the thalweg causes patterns of deposition and scour to be out-of-phase with the meander geometry of the active channel. In more severe cases, pools form in straight reaches while riffles form along the concave meander bends with several pool-riffle sequences may occurring within one meander form. This out-of-phase phenomena is due to the differences in relaxation time between fluvial features of differing spatial scale (see Section 8.0).

The phased response may also be related to geomorphic thresholds within the channel system. Morisawa and Laflure (1979), observed an initial lag in the response of mesoscale features to alteration in the driving mechanism associated with urban development. It was noted that initially little change in the rate of geomorphic activity is experienced, the rate of change in fluvial forms then accelerate rapidly toward a maximum rate. If the disturbance is held constant, equilibrium concepts maintain that the system will asymptotically approach a new equilibrium state in accordance with predictions using the rate law (Thorn and Welford, 1994).

The mutual adjustment of micro-, meso- and macroscale features is determined by complex inter-relationships between these various forms. This inter-dependence may be illustrated using the Manning Equation,

$$Q = (A\, R^{2/3}\, S^{0.5})/n$$

in which Q is the rate of flow, A is the cross-sectional area of the channel, R is the hydraulic radius (defined as the wetted perimeter P divided by A), S is the longitudinal channel slope, and 'n' is a friction factor (a composite of particle and form roughness). An increase in Q associated with urbanization initially causes the thalweg to straighten thereby increasing S. Since the hydraulic geometry (A and R) parameters have not yet adjusted, the channel responds by increasing velocity (Q=vA; where v is the average primary flow velocity). The increase in velocity is translated into an increase in shear stress on the boundary materials. Erosion of these materials causes the channel to widen thus altering A and R which represents the second phase of the adjustment process. The channel will then enter into the third phase of the adjustment process through re-adjustment of the roughness and slope parameters. The adjustment process is iterative and the final channel form will depend upon the nature of the sediment supply relative to the competence of the channel and the geology of the system (valley slope and depth to bedrock).

From these discussions it is apparent that the management of the fluvial system based on the identification and interpretation of any one group of features, e.g. mesoforms, in isolation of features of other scales, may be misleading. However, there are some measurement issues that must also be considered. The spatial and temporal scales characterizing microforms makes monitoring of these features difficult, costly and their interpretation complex. Conversely, the temporal scale associated with the measurement of the change in macroform dimensions is too large to be of practical value as a management tool. On the other hand, the dimensions and relaxation times ascribed to mesoforms are relatively well suited for the purposes of planning and design. Consequently, the geomorphic survey program was designed to characterize mesoforms with an understanding of the micro- macroform context within which they were observed.

Ideally, the sample set of fluvial features to be collected and assessed, given the spatial and temporal vagaries described in Section 8.0, would be the entire fluvial system at time intervals dictated by the relaxation time of the features of interest. Recent advances in Large Scale Photogrammetry (LSP) appear to be promising in this regard. Unfortunately, this tool is still in the development stage and despite its many advantages, it remains relatively expensive to apply on a basin wide basis primarily because of costs associated with development of the aerial photography, field proofing and computer software development.

Surveys of geomorphic forms using traditional geodetic and geomorphic survey approaches, while not comparable to the LSP technique in detail and spatial scope, can be practically applied to the measurement of micro-, meso- and macroforms on a basin wide basis. However, in order to minimize data collection requirements using this approach and maximize the utility of the information, a survey protocol based on the definition of Response Segments (RSs) or 'like' reaches is typically employed. In this approach the main channel and its principal tributaries (as defined by a minimum effective drainage area or an equivalent criteria), are mapped into reaches of common morphology (as defined within acceptable limits of variance). The rationale behind this approach is that channel form is related to process and that reaches having a common morphology will also behave in a similar manner given a perturbation in the driving mechanisms controlling channel form. The key to the effective application of this approach is the definition of morphologically 'like' reaches.

9.2 RESPONSE SEGMENT APPROACH

Using the three general channel types described previously:

◊ alluvial (AL);
◊ rock bed (RB); and,
◊ rock controlled (RC);

it is possible to map the entire stream channel system along the main branch and its tributaries. The parameters defining the limits to the mapping exercise are provided in Table 9.1.

Table 9.1. Criteria for the Mapping of 'Like' Reaches

Parameter	Acceptable Variance	
	Minimum	Maximum
Lineal Distance	20 x W_{BFL} in straight reaches or 2λ in meandering reaches	
Flow Rate		a 10% increase in flow rate or a 10% change in basin imperviousness
Drainage Area	1.0 mi^2 (effective drainage area)	

A tiered approach is used to develop the map of RS as follows:

- define potential RSs based on a desk top review of aerial and oblique photographs, land use maps, topographic, hydrographic and physiographic maps, existing reports and anecdotal information;
- using a synoptic level survey, refine the map of RSs; and,
- walk the Creek to finalize the mapping.

For smaller watersheds the micro-, meso- and macroforms within each RS would be surveyed along representative channel segments. However, this approach may be impractical for application on a regional basis or to larger watersheds due to timing and cost constraints. Consequently, an alternative approach, based on the development of empirical relations describing fluvial parameters as a function of basin attributes, may be considered as described in Section 10.0. The data requirements for this approach are described in the following Sub-Section.

9.3 MESO AND MACROFORM PARAMETERS

In this latter approach, historic sections are located within each of the 3 channel types. Historic sections are defined as reaches where:

i) geodetic surveys of cross-sections have been previously completed;
ii) the tributary area has been developed-out for sufficient time for the mesoforms to have completed the majority of the adjustment process. Estimates of the relaxation time for mesoform features assuming complete buildout of the watershed are provided in Table 9.2.

Table 9.2 Estimated Relaxation Period For Mesoform Features

Channel Class	Relaxation Period (Years)
Alluvial (AL)	10 – 55
Rock Bed (RB)	10 – 55
Rock Controlled (RC)	Not Defined (use 55)

The meso and macroforms and related survey measurements include:

a) channel cross-section ordinates;
b) bank material classification of by stratigraphic unit;
c) bank material resistance to scour by stratigraphic unit;
d) substratum classification;
e) substrate particle size;
f) longitudinal channel slope;
g) planimetric mapping of bed forms;
h) estimates of flow at the time of the survey;
i) description of riparian vegetation;
j) description of past evidence of Channelization;
k) assessment of channel stability and mode of alteration; and,
l) estimates of hydraulic parameters.

In order to assess channel stability, a Rapid Geomorphic assessment (RGA) Form has been developed specifically for urban watersheds (Table 9.4. This approach uses a Stability Index (SI) which is applied over a reach length of 20 bankfull channel widths in straight reaches and 2 meander wavelengths in meandering channel systems. The Index is defined as:

$$\mathbf{SI = (AI + DI + WI + PI)/m}$$

where m=4, AI, DI, WI, and PI are the normalized values of the aggradation, degradation, width enlargement and planimetric indices, respectively. The normalized value for each of the four FORM/PROCESS categories (Table 9.3: column 1) is computed as the sum of the indices listed under GEOMORPHIC INDICATORS (Table 9.3: column 2) for each FORM/PROCESS catageory for which a Yes determination is reported in the PRESENT column (Table 9.3: column 3) divided by 'n' which is the number of indices used for each FORM/PROCESS category. For example, there are ten indices in the

Table 9.3 Rapid Geomorphic Assessment Approach For Application To Response Segements

FORM/ PROCESS	GEOMORPHIC INDICATOR	PRESENT		INDEX
		No	Yes	
EVIDENCE OF AGGRADATION (AI)	1. lobate bars 2. coarse material in riffles embedded 3. siltation of pools 4. medial bars 5. accretion on point bars 6. poor longitudunal sorting of bed materials 7. deposition of sediment in the overbank zone	√ √ √ √	√ √ √	3/7=0.43
EVIDENCE OF DEGRADATION (DI)	1. exposed bridge footing(s) 2. exposed sanitary sewer/gas pipelines/etc 3. elevated storm sewer outfall(s) 4. undermined gabion baskets/aprons/etc. 5. scour pools d/s of culverts/stormsewers 6. cut faces on bar forms 7. head cutting due to knick point migration 8. terrace cut through older bar material 9. suspended armor layer visible in bank 10. channel worn into undisturbed overburden	n/a √ √ √ √	√ √ √ √ √	5/9=0.56
EVIDENCE OF WIDENING (WI)	1. fallen/leaning trees/fence posts 2. occurrence of Large Organic Debris 3. exposed roots on trees 4. basal scour on inside meander bends 5. basal scour on both sides of the channel in riffle sections 6. gabion baskets/concrete walls/etc. out flanked 7. length of channel with basal scour > 50%	√ √ √	√ √ √ √	4/7=0.57
EVIDENCE OF PLANIMETRIC ADJUSTMENT (PI)	1. formation of chutes 2. evolution of single thread channel to multiple 3. evolution of pool-riffle to low bed profile form 4. cutoff channels 5. formation of islands 6. thawleg alignment out of phase with meander geometry 7. bar forms poorly formed/re-worked/removed	√ √ √ √	√ √ √	3/7=0.43
STABLILITY INDEX		SI=(.43+.56+.57+.43)/4 =0.5		

GEOMORPHIC INDICTATORS column asigned to the DI index, consequently, n=10 for this category. If an index is not applicable than it is discarded from the evaluation and 'n' is reduced by 1 for each discarded index. For example, if there are no bridges in the reach then index No. 1 "exposed bridge footing(s)" under "EVIDENCE OF DEGRADATION (DI)" is not applicable and the observer should record an n/a opposite this index, reduce 'n' to 9 and move to the next index and repeat the exercise.

In the example shown in Table 9.3, the Stability Index was determined to be SI=0.5. This is intrepreted according to Table 9.4 to suggest that the channel is a process of adjustment. The Table also indicates that the channel has or is experiencing aggadation, degradation, widening and planimetric form adjustment over the survey reach. It is important to note that the Index does not provide a measure of the rate of geomorphic activity or whether the processes resulting in the observed forms are still actively dictating channel from or what sequence they occurred. To resolve this issues the RGA form must be used in concert with other techniques such as historic data sources peronal accounts and a knowledge of the likely response pattern. For example, this channel currently represents a RB(Al) system. However, historic survey data indicated that the

Table 9.4 Guidelines for the Interpretation of SI Values

SI Value	Interpretation	Comment
$0 \leq SI \leq 0.2$	Stable (S)	The morphologic features do not show evidence of progressive alteration and type and variance in the dimensions of morphologic features is within acceptable levels
$0.2 < SI \leq 0.4$	Transitional (T)	The type and variance of observed morphologic features indicates that the stream channel is in or about to begin the initial stages of adjustment
$0.4 < SI \leq 1.0$	In Adjustment (A)	The type of morphologic features suggests that the channel system has been de-stabilized and is in adjustment

bedrock was covered with several feet of Al material prior to urbanization. This materials was eroded by scour resulting in downcutting to the rock bed leaving evidence of degradation. Once the relatively resistant rock bed was encountered the channel began to widen and straighten leaving evidence of widening and planimetric form adjustment. Although the bar forms in the riffle sections were swept away during the downcutting period leaving exposed bedrock, widening of the channel has reduced scour potential on the bed and coarser material recruited from upstream sections has begun to form poorly sorted medial bars in the flatter portions of the survey reach. Use of the modified Morisawa and Laflure (1979) enlargement curve indicates that the mesoforms within this reach have achieved approximately 90% of the anticipated adjustment. Further, the period of time since cessation of development has been over thrity years. These data together with evidence of re-colonization of the banks by wood species indicates that the rate of geomorphic activity has declined.

The Stability Index (SI) data summarizes the identified channel stability features to indicate the current condition of the channel and the past erosion features. It is used to assist in the determination of the expected primary geomorphic process that will cause channel enlargement.

Output

One copy of the field data which includes photographs, hydraulic calculations (bankfull), grain size analysis and rapid geomorphic assessment forms will be provided to the City of Austin for review. In addition, an example of the field forms, hydraulic calculations, and grain size analysis (Table 9-5) follows this section.

FLUVIAL GEOMORPHOLOGY FIELD RECONNAISSANCE FORM

PROJECT TITLE: ____________________

DATE: ____________________

PROJECT #: ____________________

WATERCOURSE: ____________________

STATION NUMBER: ____________________

STATION LOCATION: ____________________

FIELD PARTY: ____________________

____

____

____

OVERVIEW PHOTOS:

ROLL #	PHOTO #	CAPTION

SOIL CONSISTENCE: DEFINITION OF TERMS

X1 (STICKINESS):

0 = NON-STICKY	Almost no adhesion of soil materials to fingers,
1 = SLIGHTLY STICKY	Soil material adheres to one finger but the other finger remains clean,
2 = STICKY	Soil material adheres to both fingers and thumb, stretches somewhat,
3 = VERY STICKY	Soil material strongly adheres to both thumb and finger but bulk of material remains intact, stretches, and
4 = EXTREMELY STICKY	Soil material preferential adheres to hand, thumb and finger, soil material structure becomes incoherent;

X2 (PLASTICITY):

0 = NON-PLASTIC	No "wire" (thread or bead) is formable by rolling the material between the palms of the hands,
1 = SLIGHTLY PLASTIC	Only short (L <1 cm) wires (> 2 mm) can be formed,
2 = PLASTIC	Longer (2 L 3 cm) wires (> 2 mm) can be formed and light pressure is needed to deform a block of molded material,
3 = VERY PLASTIC	Long (L > 3 cm) wires (< 2 mm) can be formed and moderate pressure is need to deform a block of molded material, and
4 = EXTREMELY PLASTIC	Long (L > 3 cm) wires (< 2 mm) can be formed and much pressure is needed to deform a block of molded material; and,

X3 (FIRMNESS):

0 = LOOSE	Soil material is noncoherent (comprised primarily of individual grains) and finger can penetrate bank material easily,
1 = VERY SOFT	Soil material is comprised of loose aggregates which crush with gentle pressure between the thumb and finger (friable), finger penetrates intact material with moderate pressure,
2 = SOFT	Moderate thumb and finger pressure is required to crush aggregates, finger penetrates intact material with difficulty,
3 = FIRM	Strong thumb and finger pressure is required to crush aggregates and finger can only dent intact materials, and,
4 = STIFF	Aggregates can not be broken by thumb and finger pressure and intact material can only be dented with a finger nail.

The above consistence tests are for soil material moisture contents at or slightly above "field moisture capacity" (gravitational water). The tests were also developed for materials composed of sand to clay sized particles with up to some stones within the sand-clay mattrix. The tests do not apply to materials composed of primarily gravel sized or larger particles.

PARTICLE SIZE GLOSSARY OF TERMS

Cl = Clay; Si = Silt; Sa = Sand; Gr = Gravel; Co = Cobble; Bo = Boulder; L = Loam

BANK MATERIAL COMPOSITION

Table I. Left Side (View Looking U/S)

UNIT No.	SCORE				PARTICLE SIZE (%)				SOIL CLASS	PI
	X1	X2	X3		Gr	Sa	Si	Cl		
UPPER UNIT (1)										
UNIT 2										
UNIT 3										
UNIT 4										
UNIT 5										

PI = Plasticity Index

SKETCH:

ROLL#___ PHOTO#___
ROLL#___ PHOTO#___
ROLL#___ PHOTO#___

Table II. Right Side (View Looking U/S)

UNIT	SCORE				PARTICLE SIZE (%)				SOIL CLASS	PI
	X1	X2	X3		Gr	Sa	Si	Cl		
UPPER UNIT (1)										
UNIT 2										
UNIT 3										
UNIT 4										
UNIT 5										

PI = Plasticity Index

SKETCH:

ROLL#___ PHOTO#___
ROLL#___ PHOTO#___
ROLL#___ PHOTO#___

RIPARIAN VEGETATION

Table III. Modified DU Environmental Integrity Index: Field Erosion Form

Indicator	Optimal (20-16)	Suboptimal (15-11)	Marginal (10-6)	Poor (5-1)	DU Score
Channel Alteration	No channelization or dreging present	Some chan. present; evidence of past chan. (i.e. dredging) >20 yrs., no evidence of recent chan.	New embankments present on both banks; 40-80% of stream reach channelized & disrupted	Banks hardlined; 80% of the stream reach channelized/ disrupted	
Sediment Deposition	Little or no enlargement of islands or point bars and <5% of bottom affected by sediment deposition	Some new increase in bar formation, mostly from coarse Gr; 5-30% of bottom affected; slight deposition in pools	30-50% of bottom affected by new deposits of Gr and Sa; fine deposits over coarse sed. in riffle section; presence of lobate bars; moderate deposition in pools	Thick deposits of Sa and fines, increased bar development; low pool:riffle length ratio; pools shallow (filled with fines); bed material poorly sorted	
Embedded-ness	Gr, Co, and Bo particles are 0-25% embedded in fine sediment mattrix	Gr, Co, and Bo particles are 25-50% embedded in fine sediment mattrix	Gr, Co, and Bo particles are 50-70% embedded in fine sediment mattrix	Gr, Co, and Bo particles are >70% embedded in fine sediment mattri	
Condition of Banks	Banks stable; <30% of channel length actively eroding (confined to concave meander bend)	Stressed: 1-2 geomorphic indicators of instability are present; 30-50% of channel length actively eroding	In-Adjustrment: 40-60% of channel length is actively eroding;, >2 geomorphic indicators present	In-Adjustment (high rate of geomorphic activity): >4 geomorphic indicators of instability present	
Bank Vegetation Protection	>90% streambank surface covered with vegetation	70-90% streambank surface covered with vegetation	50-90% streambank surface covered with vegetation	<50% streambank surface covered with vegetation	

GEOMORPHIC INDICATORS OF CHANNEL STABILITY

EVIDENCE OF AGGRADATION:
- Presence of lobate bars
- Fine particluate matter over coarse sediments in riffle section
- siltation of pools
- medial bar formation

EVIDENCE OF DEGRADATION:
- Exposed brudge footing/elevated storm sewer apron
- exposed utility lines
- undermined gabion/concrete walls
- headcutting due to niche point migration

EVIDENCE OF WIDENING:
- Presence of leaning trees
- presence of LOD jams (in some stream types)
- % of channel length experiencing basal scour
- active basal scour along both sides of the channel in straight reaches
- scour on the convex meander bank

EVIDENCE OF PLANIMETRIC FORM ADJUSTMENT:
- Riffle:Pool lenght ratio out of range according to channel type
- Evolution of single thread channel to multi-channel/braided form
- presence of chutes
- presence of cutoff channels
- formation of Islands

CHANNEL HYDRAULIC AND PLAN FORM GEOMETRY

SKETCH:

ROLL# ___ PHOTO# ______
ROLL# ___ PHOTO# ______
ROLL# ___ PHOTO# ______
ROLL# ___ PHOTO# ______

FIELD CLASSIFICATION OF EROSION PROCESSES

SHEAR DOMINATED FLUVIAL FORMS		PRESENT
Smoothed banks remaining after the passage of a flood		
Frequent overhangs along the length of the channel		
Surficial slumping of the blocks which topple or slide into the stream or lie at the bank toe but remain largely intact (typically with grasses continuing to grow on the original top side of the block)		
FALLING STAGE DOMINATRED FLUVIAL FORMS		
Deep seated failures, typically rotational slumps		
Arc shaped tension craks in the table land near the top of bank but set back further from the edge than noted for surficial failures		
Failed materia in the form of a slurry (bank materials having lost their original structure)		
NON-FLUVIAL PROCESSES		
Physical Weathering	Expansion-Contraction, e.g. freeze-thaw/wet-dry: cracks and sluffing of a thin veneer of surficial material	
	Soil Piping	
Bio-Weathering	Livestock trampling of banks and/or over grazing of riparian vegetation	
	Borrowing animals	
Chemical Weathering: presence of solutional forms		
Pluvial Weathering: pot marks and riverlets down bank wall		

ROSGEN CLASSIFICATION

Table V. Single Thread or Mutliple Channel System

SINGLE:	MULTIPLE:

Table VI. Entrenchment Ratio (R_E)

W_{FPA}	W_{BFL}	R_E	CLASS
			ENTRENCHED (1.0 R_E 1.4)
			MODERATELY ENTRENCHED (1.41 R_E 2.2)
			SLIGHTLY ENTRENCHED (R_E > 2.2)

W_{FPA} = flood plain width (m) at $2D_{BFL}$; W_{BFL} = bankfull width (m); $R_E = W_{FPA}/W_{BFL}$

Table VII. Bankfull Channel Width/Depth Ratio ($R_{W/D}$)

W_{BFL} (m)	D_{BFL} (m)	CLASS	$R_{W/D}$
		LOW ($R_{W/D}$ 12)	
		MODERATE/HIGH ($R_{W/D}$>12)	
		VERY HIGH ($R_{W/D}$>40)	

D_{BFL} = bankfull channel depth; $R_{W/D} = W_{BFL}/D_{BFL}$

Table VIII. Hydraulic Sinuosity Index (R_{HSI})

V_L (m)	C_L (m)	R_{HSI}

V_L = VALLEY LENGTH; C_L = CHANNEL LENGTH; $R_{HSI} = C_L/V_L$

Table IX. Substrate Composition

SUBSTRATE CLASS	AERIAL COVER (%)	D_{50} (mm)
DETRITUS		
MUCK		
CLAY		
SILT		
SAND		
GRAVEL		
COBBLE		
BOULDER		

Table X. Composition of Substratum (Intact Bed Material)

SUBSTRATUM CLASS	AERIAL COVER (%)	D_{50} (mm)
CLAY		
SILT		
SAND		
GRAVEL		
COBBLE		
BOULDER		
MARL		
ROCK		

Table XI.. Channel Longitudinal Slope (C_S)

V_S (m/m)	R_{HSI}	C_S (m/m)

C_S = LONGITUDINAL CHANNEL SLOPE; $C_S = V_S / R_{HSI}$

Table XIII. Ancillary Cross-Sectional Data

W_{BFL} (m)	D_{BFL} (m)	W_{FPA} (m)	SUBSTRATE	C_S (m/m)	R_{HSI}

DISCHARGE MEASUREMENT

Table XIII. Manning's Formula

x (m)	t (sec)	v (m/s)	A (m^2)	P (m)	R (m)	Q (m^3s^{-1})	n

X = longitudinal distance;
t = travel time;
v = flow velocity;
A = cross-sectional area
P = wetted perimeter;
R = hydraulic radius;
Q = discharge rate;
n = Manning's roughness factor

Table 5. **Rapid Geomorphic Assessment Approach For Application To Response Segements**

FORM/ PROCESS	GEOMORPHIC INDICATOR	PRESENT		INDEX
		No	Yes	
EVIDENCE OF AGGRADATION (AI)	1. lobate bars 2. coarse material in riffles embedded 3. siltation of pools 4. medial bars 5. accretion on point bars 6. poor longitudunal sorting of bed materials 7. deposition of sediment in the overbank zone			
EVIDENCE OF DEGRADATION (DI)	1. exposed bridge footing(s) 2. exposed sanitary sewer/gas pipelines/etc 3. elevated storm sewer outfall(s) 4. undermined gabion baskets/concrete aprons/etc. 5. scour pools downstream of culverts/stormsewer outlets 6. avalanche faces on bar forms 7. head cutting due to knick point migration 8.terrace cut through older bar material 9. suspended armor layer visible in bank 10. channel worn into undisturbed overburden			
EVIDENCE OF WIDENING (WI)	1. fallen/leaning trees/fence posts 2. occurrence of Large Organic Debris 3. exposed roots on trees 4. basal scour on inside meander bends 5. basal scour on both sides of the channel in riffle sections 6. gabion baskets/concrete walls/etc. out flanked 7. length of channel with basal scour > 50%			
EVIDENCE OF PLANIMETRIC ADJUSTMENT (PI)	1. formation of chutes 2. evolution of single thread channel to multiple 3. evolution of pool-riffle to braided form 4. cutoff channels 5. formation of islands 6. thawleg alignment out of phase with meander geometry 7. bar forms poorly formed/re-worked/removed			
STABLILITY INDEX		SI		

The stability index (SI) is defined as:

$$SI = (AI + DI + WI + PI)/m$$

where m=4, AI, DI, WI, and PI are the normalized values of the aggradation, degradation, width enlargement and planimetric indices, respectively. The normalized value for each of the four FORM/PROCESS categories is computed as the sum the GEOMORPHIC INDICATORS for which a Yes determination is reported in the PRESENT column divided by n = the number of GEOMORPHIC INDICATORS used for each index. If a GEOMORPHIC INDICATOR is not applicable note n/a opposite this INDICATOR in the PRESENT column and reduce n by 1. For example, if their are no bridges in the reach then GEOMORPHIC INDICATOR No. 1 "exposed bridge footing(s)" under "EVIDENCE OF DEGRADATION (DI)" is not applicable and the observer should record an n/a opposite this INDICATOR , reduce n to 9 and move to the next INDICATOR.

Cross Section No. 52

Tannehill Branch on Sanitary Sewer Line at Givens Park at Tributary

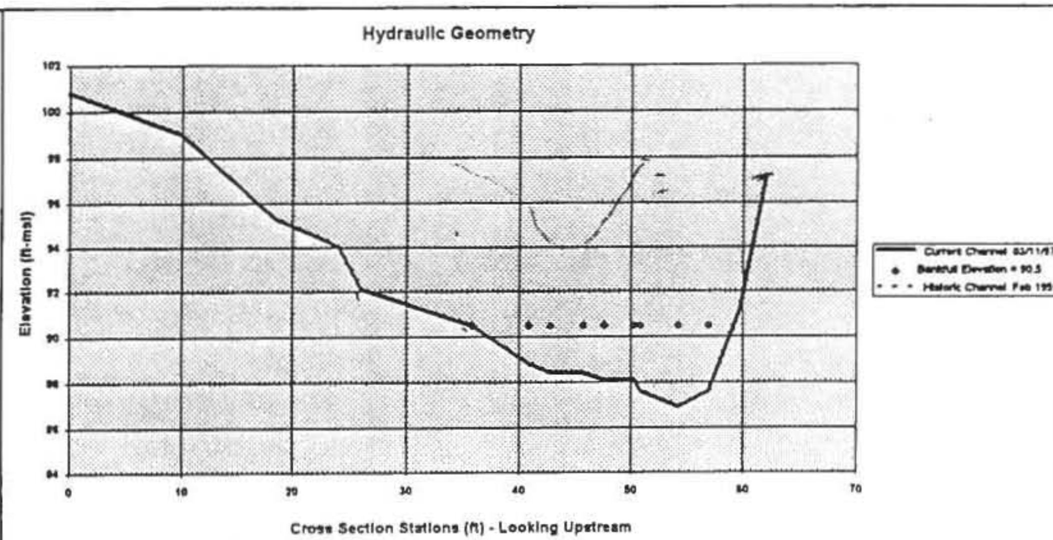
Channel Type : Alluvial Channel, Wastewater Line Sheet No. 4746

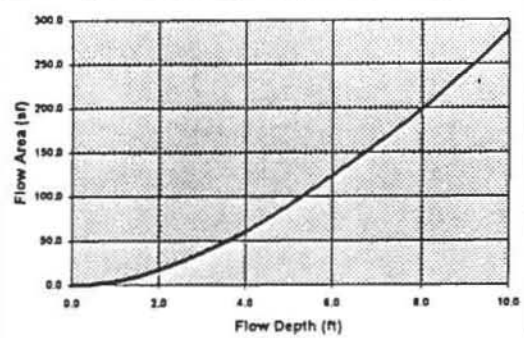
Hydraulic Flow Data [1]

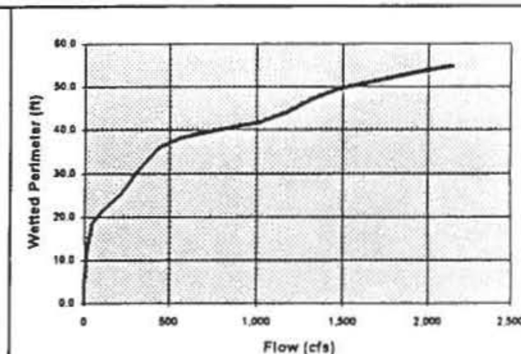
Water Surface Elevation (ft-msl)	Depth (ft)	Flow Area (ft²)	Flow Rate (cfs)	Wetted Perimeter (ft)	Hydraulic Radius (ft)	Top Width (ft)	Average Velocity (fps)	Weighted Mannings n [2]	Critical Depth [3] (ft)
86.9	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
87.4	0.5	1.1	1	4.5	0.244	4.4	1.2	0.040	0.1
87.9	1.0	4.1	8	7.1	0.570	6.7	2.1	0.040	0.4
88.4	1.5	8.7	20	12.7	0.685	11.9	2.3	0.040	0.4
88.9	2.0	16.8	47	18.5	0.909	17.4	2.8	0.040	0.6
89.4	2.5	26.0	91	20.7	1.255	19.3	3.5	0.040	0.9
89.9	3.0	36.1	147	22.9	1.576	21.2	4.1	0.040	1.1
90.4	3.5	47.1	215	25.1	1.877	23.1	4.6	0.040	1.4
90.9	4.0	59.4	279	28.5	2.083	26.2	4.7	0.042	1.5
91.4	4.5	73.3	351	32.2	2.279	29.5	4.8	0.043	1.6
91.9	5.0	88.9	437	35.8	2.484	32.7	4.9	0.045	1.8
92.4	5.5	105.9	555	38.0	2.787	34.5	5.2	0.045	2.0
92.9	6.0	123.3	696	39.2	3.141	35.2	5.6	0.046	2.3
93.4	6.5	141.0	850	40.5	3.482	35.9	6.0	0.046	2.6
93.9	7.0	159.1	1,015	41.8	3.811	36.6	6.4	0.046	2.9
94.4	7.5	177.8	1,166	44.1	4.037	38.4	6.6	0.046	3.1
94.9	8.0	197.7	1,316	46.9	4.211	40.9	6.7	0.047	3.2
95.4	8.5	218.7	1,487	49.6	4.410	43.2	6.8	0.048	3.3
95.9	9.0	240.6	1,695	51.4	4.684	44.5	7.0	0.048	3.6
96.4	9.5	263.2	1,915	53.1	4.953	45.8	7.3	0.048	3.8
96.9	10.0	286.5	2,149	54.9	5.216	47.1	7.5	0.048	4.0

* Average channel velocity and critical depth calculations do not apply above overbank elevation. [4]

Hydraulic Geometry







Bankfull Depth Hydraulic Conditions and Cross Section Data

Bankfull Flow Elevation (ft-msl)	90.5 *
Channel Slope (ft/ft)	0.0065
Max. Critical Depth Elevation (ft-msl) [4]	97.2
Maximum Evaluated Elevation (ft-msl)	97.2
Depth of Flow (ft)	3.6
Weighted Mannings n [2]	0.040
Total Flow Area (ft²)	49.5
Wetted Perimeter (ft)	25.6
Hydraulic Radius (ft)	1.936
Mannings Flow (cfs)	230.8
Average Channel Velocity (fps)	4.7
Topwidth (ft)	23.5
Critical Depth "y_c" (ft) [3]	1.4
y_c Elevation (ft-msl)	88.3

Cross Section Skew Angle (deg) = 0

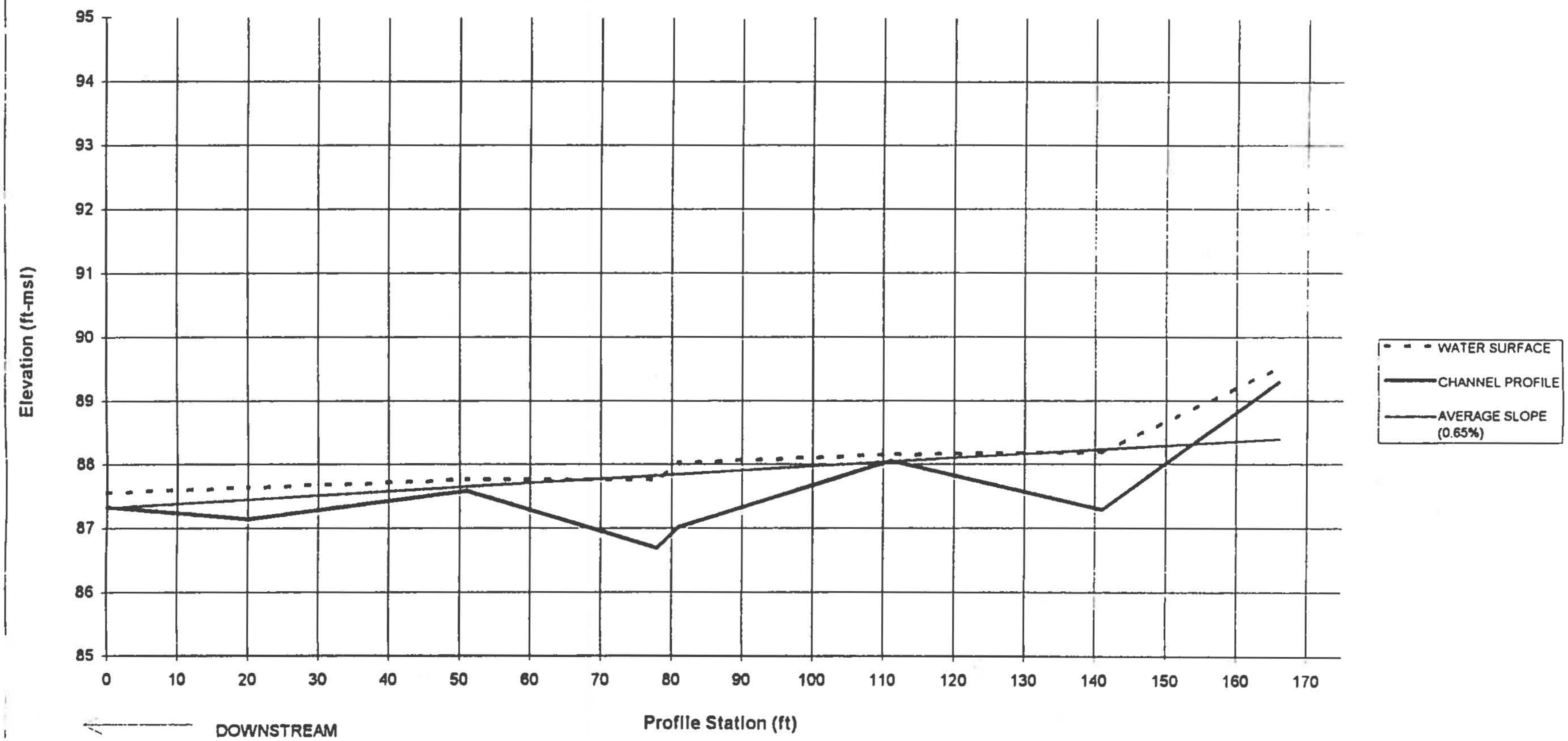
Station No. Range (Left to Right)	0 to 10	10 to 18.4	18.4 to 23	23 to 24.1	24.1 to 26.	26.1 to 35.8	35.8 to 40.9	40.9 to 42.8	42.8 to 45.7	45.7 to 47.6	47.6 to 50.3	50.3 to 50.9	50.9 to 54.3	54.3 to 57	57 to 59.8
Mannings n	0.06	0.06	0.06	0.06	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04 *
Relative Elevation (ft-msl)	100.8	99	95.3	94.3	94	92.1	90.5	88.8	88.4	88.4	88.1	88.1	87.6	86.9	87.6
Station (ft)	0	10.0	18.4	23.0	24.1	26.1	35.8	40.9	42.8	45.7	47.6	50.3	50.9	54.3	57.0
Flow Area (sf)	0.0	0.0	0.0	0.0	0.0	0.0	4.3	3.6	6.1	4.3	8.5	1.6	11.1	8.8	3.3
Wetted Perimeter (ft)	0.0	0.0	0.0	0.0	0.0	0.0	5.4	1.9	2.9	1.9	2.7	0.8	3.5	2.8	3.7
Topwidth (ft)	0.0	0.0	0.0	0.0	0.0	0.0	5.1	1.9	2.9	1.9	2.7	0.6	3.4	2.7	2.3

Station No. Range (Left to Right)	59.8 to 62															
Mannings n	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Relative Elevation (ft-msl)	91.2	97.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Station (ft)	59.8	62.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Flow Area (sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetted Perimeter (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Topwidth (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* Note: All input data are displayed in boxed areas.

1 Flow rates and velocities are based on Mannings equation.
2 Weighted Mannings n is the product of the Mannings n and wetted perimeter for each cross section segment divided by the total wetted perimeter for a specific flow depth.
3 Critical depth is based on [Q2/g = A3/Topwidth], where A = topwidth x critical depth.
4 Maximum elevation evaluated for critical depth. Critical depth is not considered applicable, using equation (see note 3), when flow depth exceeds overbank elevation.

Profile No. 52
on tributary to Tannehill Branch at givens park
Wastewater Line No. 4746



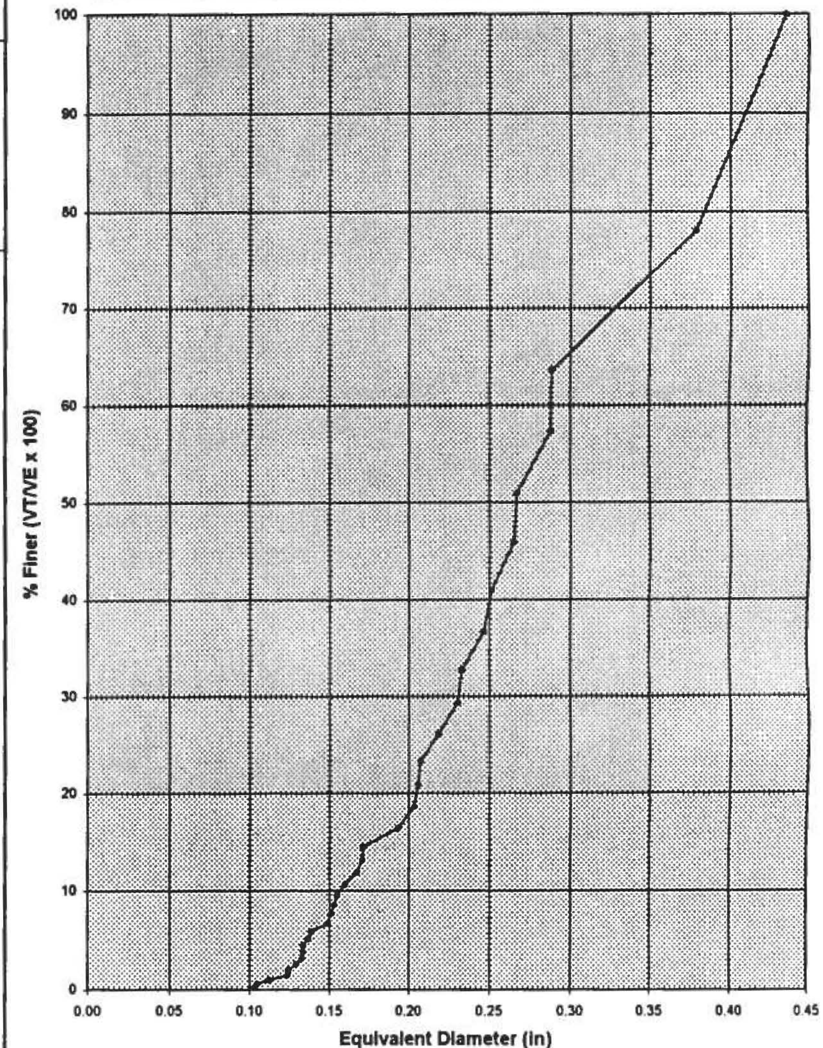
Starting Elevation (ft-msl)	87.33
Ending Elevation (ft-msl)	88.05
Starting Station	0
Ending Station	111

Profile Station Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Water Surface Elevation (ft-msl)	87.56	87.64	87.76	87.75	88.02	88.15	88.19	89.54	0	0	0	0	0	0	0	0	0	0	0	0
Thalweg Elevation (ft-msl)	87.33	87.14	87.58	86.69	87.02	88.05	87.29	89.29	0	0	0	0	0	0	0	0	0	0	0	0
Station (ft)	0	20	51	78	81	111	141	166	0	0	0	0	0	0	0	0	0	0	0	0
Average Slope Elevation	87.33	87.46	87.66	87.84	87.86	88.05	88.24	88.41	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Pebble Count Results - Cross-Section Number 52
Tannehill Branch on Sanitary Sewer Line at Givens Park at Tributary
Wastewater Line Sheet No. 4746

Unsorted Raw Data (Starting at Left Side of Channel)			Data Sorted by Equivalent Diameter in Ascending Order													
Dimension 1 Length (in)	Dimension 2 Length (in)	Dimension 3 Length (in)	Dimension 1 Length (in)	Dimension 2 Length (in)	Dimension 3 Length (in)	Major Axis Length "L" (in)	Major Axis Length "W" (in)	Breadth "H" (in)	Roundness	Flatness	Equivalent Radius (in)	Equivalent Diameter (in)	Equivalent Volume (VE) (in^3)	Cummulative Equivalent Volume (in^3)	V_E/V_T x 100
0.29	0.20	0.10	0.19	0.08	0.05	0.19	0.08	0.05	1.84	2.70	0.05	0.10	0.00	0.00	0.29
0.20	0.18	0.17	0.12	0.11	0.06	0.12	0.11	0.06	1.14	1.92	0.05	0.10	0.00	0.00	0.60
0.17	0.19	0.04	0.15	0.13	0.05	0.15	0.13	0.05	1.33	2.80	0.06	0.11	0.00	0.00	0.98
0.15	0.13	0.05	0.17	0.19	0.04	0.19	0.17	0.04	1.54	4.50	0.06	0.12	0.00	0.00	1.48
0.28	0.10	0.30	0.22	0.20	0.03	0.22	0.20	0.03	1.77	7.00	0.06	0.12	0.00	0.00	1.99
0.35	0.34	0.11	0.15	0.11	0.09	0.15	0.11	0.09	1.16	1.44	0.06	0.13	0.00	0.00	2.56
0.11	0.21	0.12	0.25	0.16	0.04	0.25	0.16	0.04	1.89	5.13	0.07	0.13	0.00	0.00	3.18
0.38	0.16	0.17	0.16	0.17	0.06	0.17	0.16	0.06	1.27	2.75	0.07	0.13	0.00	0.01	3.81
0.30	0.25	0.22	0.17	0.12	0.08	0.17	0.12	0.08	1.27	1.81	0.07	0.13	0.00	0.01	4.44
0.28	0.24	0.19	0.16	0.11	0.10	0.16	0.11	0.10	1.17	1.35	0.07	0.14	0.00	0.01	5.12
0.19	0.16	0.08	0.17	0.12	0.09	0.17	0.12	0.09	1.22	1.61	0.07	0.14	0.00	0.01	5.83
0.25	0.16	0.15	0.15	0.15	0.10	0.15	0.15	0.10	1.01	1.50	0.07	0.15	0.00	0.01	6.70
0.16	0.17	0.06	0.20	0.13	0.09	0.20	0.13	0.09	1.33	1.83	0.08	0.15	0.00	0.01	7.60
0.15	0.15	0.10	0.19	0.16	0.08	0.19	0.16	0.08	1.25	2.19	0.08	0.15	0.00	0.01	8.54
0.25	0.18	0.11	0.23	0.11	0.10	0.23	0.11	0.10	1.49	1.70	0.08	0.15	0.00	0.01	9.52
0.23	0.11	0.10	0.11	0.21	0.12	0.21	0.12	0.11	1.32	1.50	0.08	0.16	0.00	0.01	10.59
0.17	0.12	0.09	0.24	0.19	0.07	0.24	0.19	0.07	1.44	3.07	0.08	0.17	0.00	0.02	11.83
0.12	0.13	0.22	0.21	0.18	0.09	0.21	0.18	0.09	1.23	2.17	0.09	0.17	0.00	0.02	13.14
0.45	0.36	0.23	0.12	0.13	0.22	0.22	0.13	0.12	1.29	1.46	0.09	0.17	0.00	0.02	14.47
0.20	0.13	0.09	0.25	0.18	0.11	0.25	0.18	0.11	1.29	1.95	0.10	0.19	0.00	0.02	16.38
0.20	0.30	0.12	0.29	0.20	0.10	0.29	0.20	0.10	1.42	2.45	0.10	0.20	0.00	0.03	18.62
0.12	0.11	0.06	0.25	0.16	0.15	0.25	0.16	0.15	1.21	1.37	0.10	0.21	0.00	0.03	20.94
0.21	0.18	0.09	0.20	0.18	0.17	0.20	0.18	0.17	0.96	1.12	0.10	0.21	0.00	0.03	23.31
0.25	0.16	0.04	0.20	0.30	0.12	0.30	0.20	0.12	1.37	2.08	0.11	0.22	0.00	0.04	26.09
0.16	0.11	0.10	0.28	0.10	0.30	0.30	0.28	0.10	1.30	2.90	0.12	0.23	0.00	0.04	29.34
0.35	0.26	0.18	0.23	0.20	0.19	0.23	0.20	0.19	0.98	1.13	0.12	0.23	0.00	0.04	32.72
0.65	0.38	0.23	0.38	0.16	0.17	0.38	0.17	0.16	1.54	1.72	0.12	0.25	0.01	0.05	36.71
0.23	0.20	0.19	0.35	0.24	0.13	0.35	0.24	0.13	1.39	2.27	0.13	0.25	0.01	0.06	40.93
0.19	0.08	0.05	0.28	0.24	0.19	0.28	0.24	0.19	1.06	1.37	0.13	0.26	0.01	0.06	45.87
0.22	0.20	0.03	0.35	0.34	0.11	0.35	0.34	0.11	1.31	3.14	0.13	0.27	0.01	0.07	50.93
0.24	0.19	0.07	0.35	0.26	0.18	0.35	0.26	0.18	1.22	1.69	0.14	0.29	0.01	0.08	57.26
0.17	0.12	0.08	0.30	0.25	0.22	0.30	0.25	0.22	1.04	1.25	0.14	0.29	0.01	0.09	63.64
0.35	0.24	0.13	0.45	0.38	0.23	0.45	0.36	0.23	1.19	1.76	0.19	0.38	0.02	0.11	78.04
0.15	0.11	0.09	0.65	0.38	0.23	0.65	0.38	0.23	1.49	2.24	0.22	0.44	0.03	0.14	100.00

Total Equivalent Volume "V_T" 0.14



Data Summary

	Equivalent Diam. (in)	V_E/V_T x 100	Equivalent Volume (in^3)
50th Percentile	0.17	11.83	0.00
80th Percentile	0.25	36.71	0.01

10.0 URBAN DRAINAGE SYSTEM ENLARGEMENT POTENTIAL

Purpose

Determining the enlargement potential (ratio) for each like reach will provide the City with an estimate of the expected channel enlargement, sediment transport, and erosion hazard area.

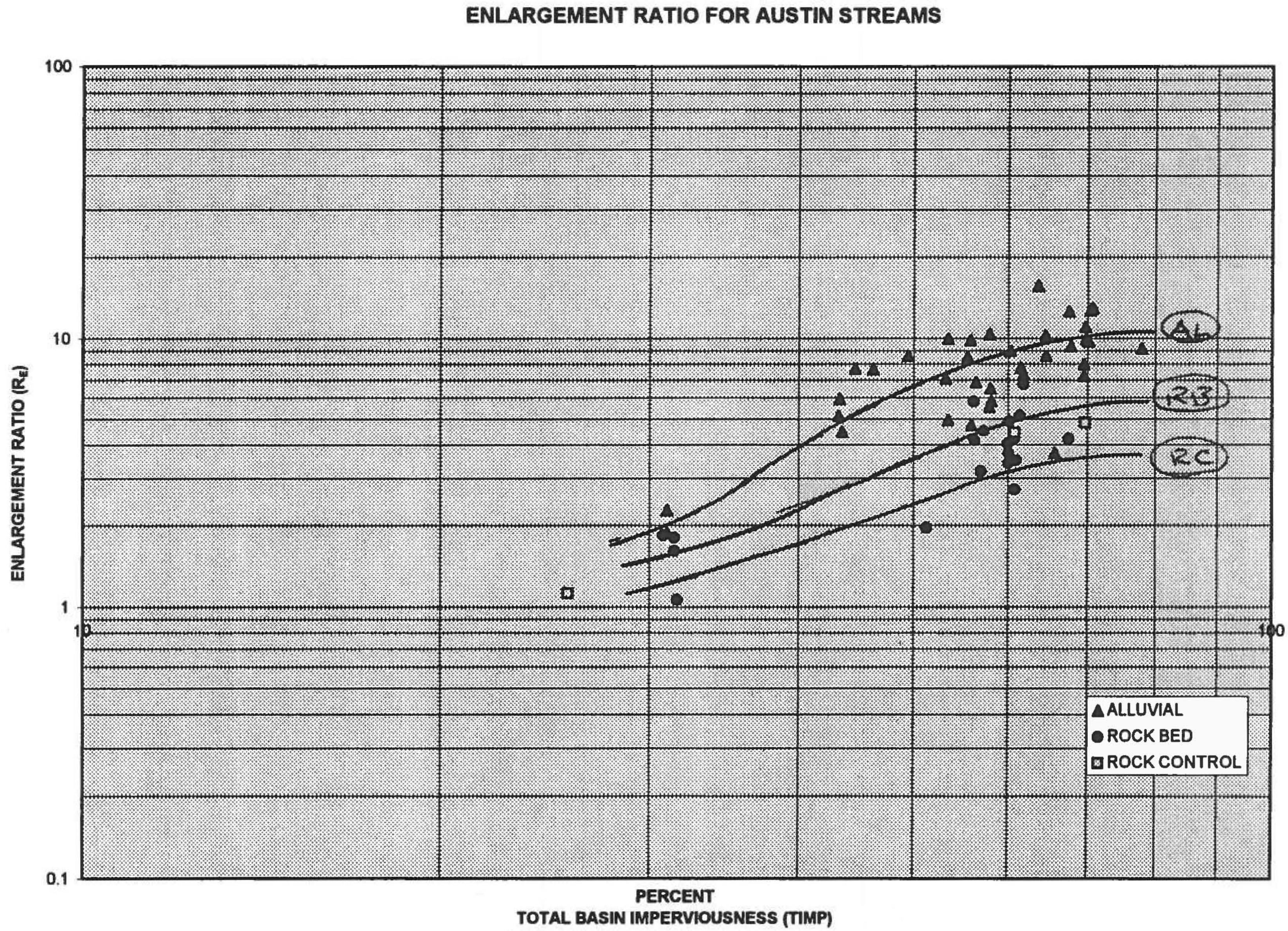
Approach

Given the complexity of bank erosion, Richards (1977) concluded that a multivariate approach is required before a state of dynamic equilibrium can be identified in a river system. This assumes that the dependent and independent variables are quantifiable and that the inter-relationship between variables can be established. Unfortunately, the state-of-the-science is such that questions concerning when and how a channel will respond to an alteration in the driving mechanisms can only be answered in a general or probabilistic manner. In this context an empirical approach based on the development and calibration of a modified version of the Morisawa and Laflure (1979) channel enlargement curve (Austin Enlargement Curve) Figure 10-1 has been proposed. The rationale behind this approach is as follows:

- the change in impervious land cover within a watershed can be used as a surrogate for the alteration in instream erosion potential;
- instream erosion potential can be adequately represented by scour;
- channel enlargement varies inversely with drainage area and the resistance of the channel boundary materials (all other factors being equal);
- that channel response to a change in the driving mechanisms controlling channel form can be adequately represented by grouping channels into three broad categories based on boundary material sensitivity to scour (see Section 8.0).

In its current form the Morisawa and Laflure (1979) channel enlargement curve is a bivariate model showing channel enlargement as a function of area greater then 5% imperviousness. When data on channel enlargement, as reported by other researchers, is plotted on the enlargement curve it is apparent that different fluvial systems have unique plotting positions. The plotting position appears to be related to the relative sensitivity of the boundary materials within which these channels are formed. For example, the enlargement curve provided in the Williamson Creek study (included here as Figure 10.2) reported data for Sawmill Creek, Ontario which is worn into thinly bedded, inter-bedded shale-limestone materials (MacRae et al., 1994), data from massive rock bed (RB) chalk and shale systems in Texas (Allen and Narramore, 1985), and the data collected for alluvial channels by Morisawa and Laflure (1979). These data indicate

FIGURE 10-1



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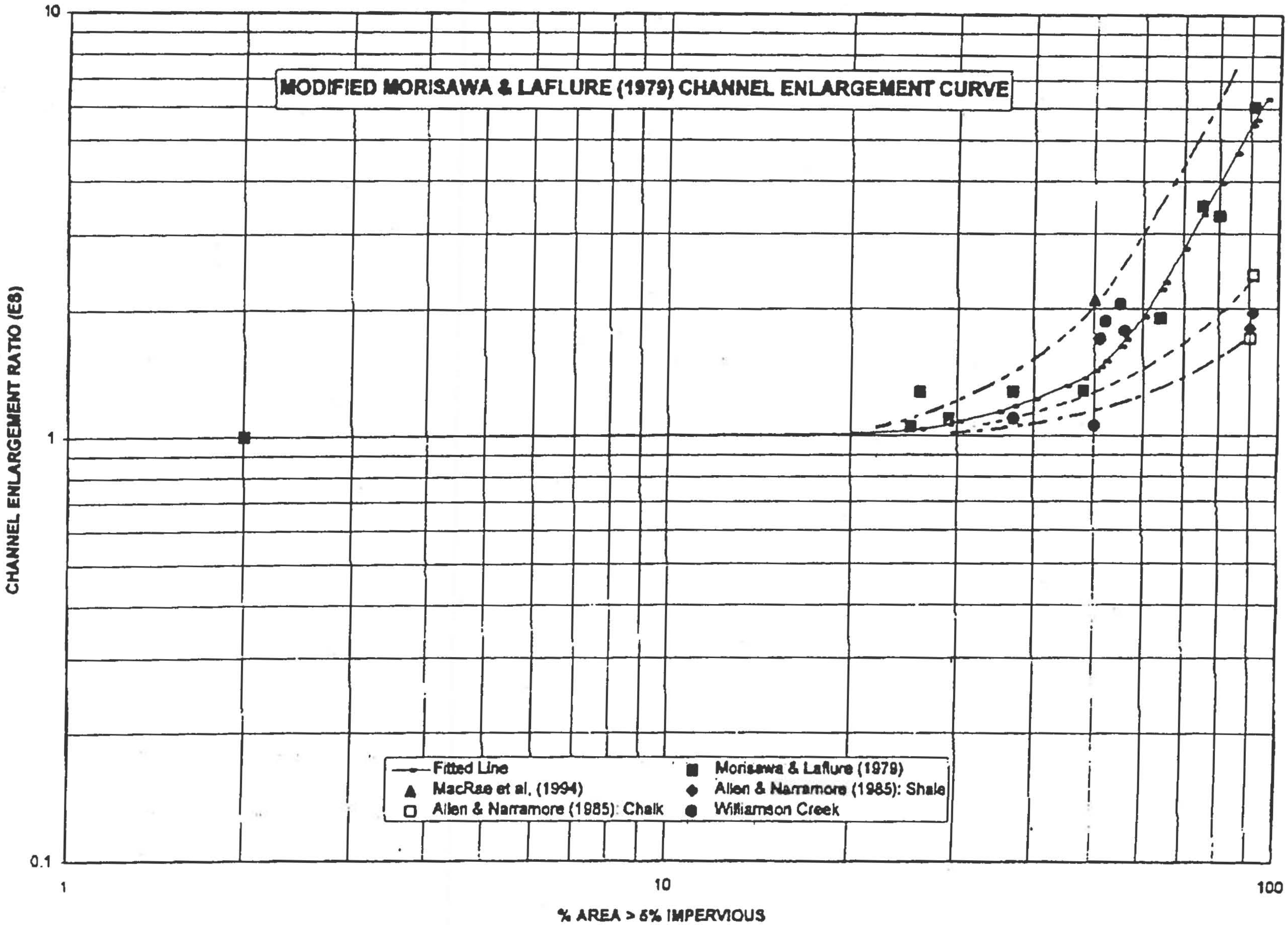

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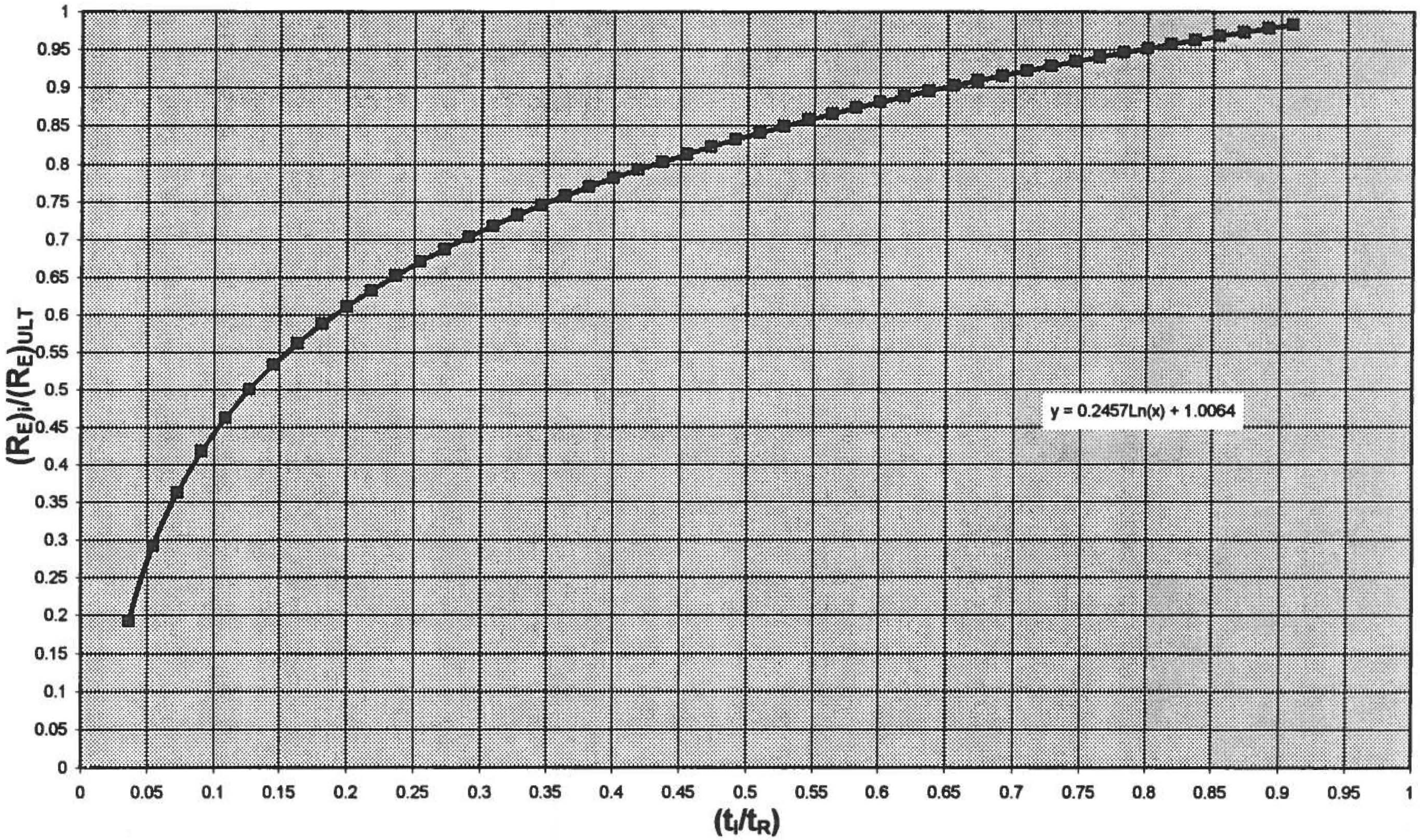
95% FIGURE 10-2

FIGURE 10-3

Hypothetical Channel Relaxation Curve in Response to an Instantaneous Disturbance



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that stream channels can be grouped according to boundary material resistance to scour and stream power. Massively bedded bedrock control streams, such as those reported by Allen and Narramore (1985), had a relatively low plotting position on the R_E versus %AREA >5% IMPERVIOUSNESS graph. Sawmill Creek, which is formed in the highly erodible material has a relatively high plotting position. The alluvial streams reported by Morisawa and Laflure (1979) plotted between these two types of boundary materials.

In this approach an enlargement curve would be developed for each of the 3 stream types from an assessment of streams in the Austin area. The geomorphic surveys undertaken for this purpose are described in the preceding Section. The channel enlargement ratio (R_E) will be calculated from these data and plotted against basin imperviousness as determined for the basin area tributary to each survey station. Enlargement curves for each stream type will be fitted through the data based on an interpretation of the geomorphic parameters measured for each plotting position. It is anticipated that the resulting graph will consist of 3 curves, one for each stream type.

One unknown in the generation of Figure 10-1 is the undocumented maintenance activities that may have occurred since the identification of the historic channel geometry. Unknown soil disturbances and channel widening may have resulted, which could show greater channel enlargement potential than expected from the impervious cover increases as the watershed developed.

A protocol for application of the graphs consists of the following steps (Table 10-1).

Table 10.1. Protocol for the Determination of Channel Enlargement Potential

ENLARGEMENT PROCESS

West Bouldin Creek, Reach 1 Example
All Tables refer to Watershed Erosion Assessment Reports

1. Input current cross-section into spreadsheet. Input bankfull depths and other parameters for current cross section (1996 or 1997). Calculate bankfull flow rates. Use photographs of section to estimate bankfull depth if non were determined in the field survey. Consider "average" bankfull depth over reach. Use slope from survey, if none determined use slope from Table 6-1, Like Reach Summary. Use Manning's "n" from survey, if not available use photographs with summer conditions (full vegetation) since the typical severe weather months of April through October occur when foliage is in full bloom.

2. Calculate $Q_{BKFL\ ACT}$ for the current condition. Using the impervious cover percentages input into the Hydrologic Analysis (Section 3, Table 3-1) select the existing 2-year peak flow value for the desired reach. Q_2 = 1379 cfs, Q_{BKFL} = 0.7 Q_2 - 368 = 597 cfs corresponds to a depth of approximately 3.7 feet (from Step 1). From field indicators, bankfull depth is approximately 3 feet. Since applying this cross section over the entire reach, average the bankfull depths (3 + 3.7)/2 = 3.3 feet.

   $$\left[(D_{BFL})_{ACT} \right]_{EXT} = 3.3 \text{ feet}$$

   From the plot in step 1 above, a bankfull area of 69 square feet can be determined from the hydraulic flow data

   $$\left[(A_{BFL})_{ACT} \right]_{EXT} = 69 \text{ square feet}$$

3. Determine average age of development from land use maps, average age of development (t_i) = 55 years.

4. Determine relaxation period from Technical Procedures Manual Table, for alluvial channel, relation period (t_R) = 55 years. Thus, channel enlargement due to land use changes is mostly complete. Compute t_i / t_R ≈ 0.98 (use as maximum for all reaches to allow for erosion at the geomorphic rate prior to development).

5. Determine existing and future watershed impervious cover from Table 2-1.

   Impervious Cover Existing % = 54 percent

Future Impervious Cover % = 54 percent

No increase in impervious cover is expected which correlates to the developed nature of the watershed, check stability Index (SI) Valve in Table 6-1 which is based on the Rapid Geomorphic Assessment form prepared for each reach. SI = 0.26 (Reach in Transition with widening identified as the primary geomorphic problem). Review photographs in Section 14 of report. Do the above conclusions make sense on relaxation and watershed build out.

6. Determine Enlargement Ratios (R_E) for the existing channel condition.

$R_{E\ EXT\ ULT} = 7.5$ from Figure 7-1
Using $t_i / t_R = 1.0$ from Step 4, go to Figure 7-2 and
determine $R_{E\ EXT} / R_{E\ EXT\ ULT} = 0.98$

$\therefore\ R_{E\ EXT} = 0.98\ R_{E\ EXT\ ULT}$
$R_{E\ EXT} = (0.98)\ (7.5) = 7.4$

7. Determine pre-development bankfull channel area.

$$A_{BFL\ PRE} = \frac{A_{BFL\ EXT}}{R_{E\ EXT}} = \frac{69}{7.4} = 9.3 \text{ square feet.}$$

Channel was excavated based on alignment and channel section, thus enlargement is not directly based on natural processes responding to watershed development.

8. Compute ultimate future bankfull channel area.

$A_{BFL\ FUT\ ULT} = 9.3\ (A_{BFL\ PRE}) \times R_{E\ FUT\ ULT}$

Obtain $R_{E\ FUT\ ULT}$ from Figure 7-1 based on impervious cover of 54% per Table 2-1.

$R_{E\ FUT\ ULT} = 7.5$

$A_{BFL\ FUT\ ULT} = 9.3 \times 7.5 = 70$ square feet

9. Compute difference between $A_{BFL\ FUT\ ULT}$ and $A_{BFL\ EXT\ CUR}$. Difference is 1 square foot, use this number to determine sediment yield.

10. Determine the appropriate enlargement process. From the RGA form, and noted in Table 6-1, the primary geomorphic process is widening. With several culverts bisecting the reach and acting as grade control structures, the channel would not likely degrade. Apply the channel enlargement to the width, draw on the cross section from Step 1.

11. Channel is maintained, but some slopes in the reach are near vertical and poorly vegetated. Other slopes are well vegetated and appear stable. Assume bank slopes remain the same. If bank slopes are very steep, then bank widening will remove additional soil above the enlarged bankfull active channel.

12. Sediment Yield is equal to the reach length multiplied by the total bank loss. Thus reach length from Table 6-1 is 4,900 feet. Sediment Yield = (1)(4900) = 4,900 cubic feet over the study period. Assume 120 pounds per cubic foot, so estimated weight is 294 tons.

13. Top width does not increase since 1 square foot of bank loss should not affect slopes. If significant bank loss occurs at a section, use current slope as future bank slope. In addition, increase in bankfull area will be applied equally to each bank.

14. Management approach would be a Type 1 approach, i.e., specific problems should be dealt with locally since watershed is fully developed and the creek has basically adjusted to satisfy the ultimate future channel condition. However, some potential for slope failures does exist as evidenced by the City constructed project at Hillside Apartments. Thus, localized slope protection projects could be required over the study period.

Output

The estimated channel enlargement will be computed with the corresponding sediment yield and top width increase. One cross section per like reach will be used to perform the calculations apply to the entire reach. Thus, the output should be used as a planning tool only because of variability in channel cross section, soils, and bank vegetation. See the attached tables for examples of report output.

ENLARGEMENT RATIO CALCULATIONS
FORT BRANCH

REACH #	STREAM TYPE	REACH SLOPE (%)	REACH LENGTH (FT.)	S.I. VALUE	Ti (YEARS)	TR (YEARS)	Ti/TR	D BFL ACT (SURVEY)	Q2 (CFS)	Q BFL ACT (CFS)	D BFL ACT (FT.)	AVG D BFL (FT.)	A BFL ACT,EXT (SQ. FT.)	EXIST IMP CVR (%)	FUT IMP CVR (%)	RE EXT ULT
1	Alluvial	0.67	600	0.43	42	55	0.75	1.5*	1337	568	5.2	5.2*	107	43.4	50.7	5.0
2	Rock Bed	0.50	9,220	0.44	42	55	0.75	2.1*	1262	516	5.7	5.7*	135	45.2	50.4	2.9
3	Alluvial	0.83	4,580	0.48	42	55	0.76	1.7	1141	431	3.8	2.8	63	48.4	50.3	6.3
4	Rock Bed	0.72	5,560	0.47	42	55	0.76	3.0	951	298	3.3	3.2	39	53.8	54.0	7.8
5	Alluvial	0.72	2,500	0.49	42	55	0.76	2.6	903	264	2.8	2.7	33	55.5	56.1	8.0
6	Structural	1.14	1,750	0.00	42	55	0.76	0.0	683	110	0	0.0	0	58.7	60.5	3.1
7	Alluvial	1.29	1,550	0.30	42	55	0.76	2.3	641	81	1.5	1.9	21	61.0	63.2	9.2
8	Structural	1.00	2,200	0.30	42	55	0.76	No data	552	18	1.1	1.1	7	67.3	70.0	3.6
9	Alluvial	1.04	1,350	0.28	45	55	0.82	1.6	449	**	1.6	1.6	9	69.2	73.3	10.0
1	Alluvial	0.62	3,850	0.25	42	55	0.76	1.6	269	**	1.6	1.6	12	40.6	44.8	4.1

* Indicates inset channel measurement and not active bankfull channel.

Use of Q bkfl alone in Reach 1 and 2 compensates somewhat for planned upstream channelization in Reach 3

** Bankfull equation based on flow not considered as drainage area is outside limits of equation.

ENLARGEMENT RATIO CALCULATIONS
FORT BRANCH

REACH #	RE EXT/ RE EXT ULT	RE EXT	A BFL PRE (SQ. FT.)	RE FUT ULT	A BFL FUT, ULT (SQ. FT.)	DIFF A BFL (SQ. FT.)	BANK RETREAT (SQ. FT.)	TOTAL BANK LOSS (SQ. FT.)	PRIMARY GEOMORPH PROBLEM	SEDIMENT YIELD (TONS)	SEDIMENT YIELD (TONS/LF)	TOP WIDTH INCREASE (FT.)	RE FUT ULT/ RE EXT CUR
1	0.94	4.7	23	7.0	159	52	9	61	Aggradation	2209	3.68	3.5	1.49
2	0.94	2.7	50	3.5	173	38	20	58	Degradation, Widening	32269	3.50	4	1.28
3	0.94	5.9	11	6.9	73	10	10	20	Widening, Degradation	5607	1.22	0	1.17
4	0.94	7.3	5	7.9	42	3	0	3	Widening, Degradation	1008	0.18	0	1.08
5	0.94	7.5	4	8.2	36	3	5	8	Widening, Degradation	1198	0.48	1	1.09
6	0.94	2.9	0	3.2	0	0	0	0	None	0	0.00	0	1.10
7	0.94	8.6	2	9.8	24	3	2	5	Widening, Degradation	446	0.29	1.5	1.13
8	0.94	3.4	2	3.8	8	1	0	1	Aggradation	114	0.05	0	1.12
9	0.95	9.5	1	10.1	10	1	1	2	Widening, Degradation	127	0.09	0	1.06
1	0.94	3.9	3	5.5	17	5	3	8	Widening	1877	0.49	0	1.43

Cross Section No. 26
Fort Branch 200 ft D/S Springdale Rd.
Channel Type : Alluvial Channel, Wastewater Line Sheet No. 6313

REACH 3 - ALLUVIAL CHANNEL. EXISTING GRADE CONTROL STRUCTURES PREVENT LARGE DOWNCUTTING. EXPECT PRIMARILY WIDENING AS EVIDENCED BY PHOTOS RGA.

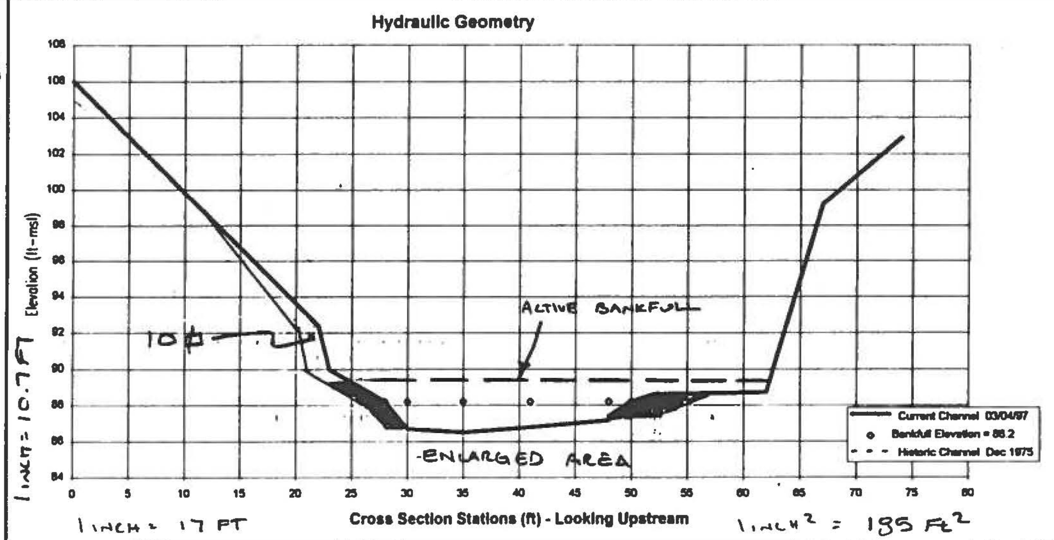
Hydraulic Flow Data [1]

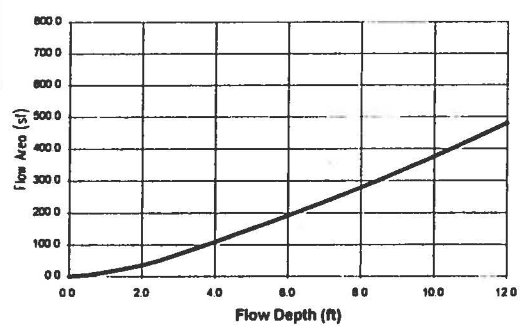
Water Surface Elevation (ft-msl)	Depth (ft)	Flow Area (ft^2)	Flow Rate (cfs)	Wetted Perimeter (ft)	Hydraulic Radius (ft)	Top Width (ft)	Average Velocity (fps)	Weighted Mannings n [2]	Critical Depth [3] (ft)
86.5	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
87.0	0.5	4.5	7	15.0	0.300	14.9	1.5	0.035	0.2
87.5	1.0	13.5	35	19.8	0.683	19.3	2.6	0.035	0.5
88.0	1.5	23.7	83	22.0	1.076	21.2	3.5	0.035	0.8
88.5	2.0	35.0	144	25.3	1.382	24.3	4.1	0.035	1.0
89.0	2.5	51.2	207	37.6	1.362	36.4	4.0	0.035	1.0
89.5	3.0	69.8	329	39.6	1.761	38.0	4.7	0.036	1.3
90.0	3.5	89.2	472	41.7	2.141	39.6	5.3	0.037	1.6
90.5	4.0	109.1	639	42.8	2.552	40.1	5.9	0.037	2.0
91.0	4.5	129.3	822	43.9	2.947	40.5	6.4	0.038	2.3
91.5	5.0	149.6	1,019	45.0	3.328	41.0	6.8	0.038	2.7
92.0	5.5	170.2	1,228	46.1	3.696	41.4	7.2	0.039	3.0
92.5	6.0	191.0	1,440	47.2	4.045	42.0	7.5	0.039	3.3
93.0	6.5	212.3	1,629	48.7	4.356	43.0	7.7	0.040	3.5
93.5	7.0	234.1	1,825	50.2	4.659	44.1	7.8	0.042	3.8
94.0	7.5	256.4	2,028	51.7	4.954	45.1	7.9	0.043	4.0
94.5	8.0	279.2	2,238	53.2	5.243	46.2	8.0	0.044	4.2
95.0	8.5	302.5	2,456	54.8	5.525	47.2	8.1	0.045	4.4
95.5	9.0	326.4	2,681	56.3	5.801	48.3	8.2	0.046	4.6
96.0	9.5	350.8	2,914	57.8	6.073	49.3	8.3	0.047	4.8
96.5	10.0	375.7	3,154	59.3	6.339	50.3	8.4	0.047	5.0
97.0	10.5	401.1	3,402	60.8	6.600	51.4	8.5	0.048	5.1
97.5	11.0	427.1	3,657	62.3	6.858	52.4	8.6	0.049	5.3
98.0	11.5	453.6	3,921	63.8	7.111	53.5	8.6	0.050	5.5
98.5	12.0	480.6	4,192	65.3	7.361	54.5	8.7	0.050	5.7
99.0	12.5	508.1	4,472	66.8	7.607	55.6	8.8	0.051	5.9
99.5	13.0	536.2	4,735	68.6	7.816	57.1	8.8	0.052	6.0
100.0	13.5	565.2	4,992	70.6	8.002	58.8	8.8	0.053	6.1
100.5	14.0	595.0	5,262	72.6	8.190	60.6	8.8	0.053	6.2
101.0	14.5	625.7	5,544	74.7	8.380	62.3	8.9	0.054	6.3
101.5	15.0	657.3	5,839	76.7	8.571	64.1	8.9	0.055	6.4
102.0	15.5	689.8	6,147	78.7	8.764	65.8	8.9	0.056	6.5
102.5	16.0	723.2	6,467	80.7	8.958	67.6	8.9	0.056	6.6

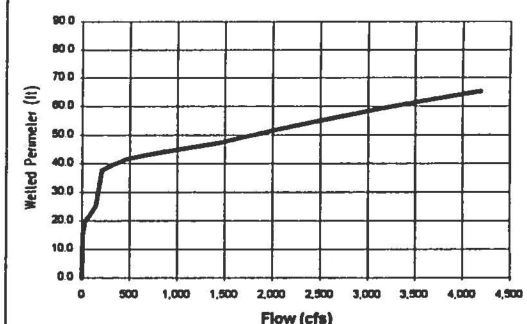
BANK LOSS PER GEOMORPHIC = 10 #
BANK LOSS PER BANK RETREAT = 10 #
TOTAL = 20 #

TOP WIDTH ENLARGEMENT 6 FT

* Average channel velocity and critical depth calculations do not apply above overbank elevation. [4]







Bankfull Depth Hydraulic Conditions and Cross Section Data

Bankfull Flow Elevation (ft-msl)	88.2 *
Channel Slope (ft/ft)	0.0061
Max. Critical Depth Elevation (ft-msl) [4]	102.9
Maximum Evaluated Elevation (ft-msl)	102.9
Depth of Flow (ft)	1.7
Weighted Mannings n [2]	0.035
Total Flow Area (ft^2)	26.0
Wetted Perimeter (ft)	22.9
Hydraulic Radius (ft)	1.224
Mannings Flow (cfs)	106.5
Average Channel Velocity (fps)	3.6
Topwidth (ft)	22.0
Critical Depth "y_c" (ft) [3]	0.9
y_c Elevation (ft-msl)	87.4

Cross Section Skew Angle (deg) = 0

Station No. Range (Left to Right)	0 to 22	22 to 23	23 to 28	28 to 30	30 to 35	35 to 41	41 to 48	48 to 48	48 to 50	50 to 52	52 to 62	62 to 67	67 to 74	74 to 74	74 to 74
Mannings n	0.08	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.08	0.08	0.08	0.08 *
Relative Elevation (ft-msl)	106	92.4	90	88.2	86.7	86.5	86.8	87.2	87.4	88.2	88.6	88.7	99.2	102.9	102.9
Station (ft)	0	22.0	23.0	28.0	30.0	35.0	41.0	48.0	48.0	50.0	52.0	62.0	67.0	74.0	74.0
Flow Area (sf)	0.0	0.0	0.0	1.5	8.0	9.3	8.4	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Wetted Perimeter (ft)	0.0	0.0	0.0	2.5	5.0	6.0	7.0	0.2	2.2	0.0	0.0	0.0	0.0	0.0	0.0
Topwidth (ft)	0.0	0.0	0.0	2.0	5.0	6.0	7.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0

Station No. Range (Left to Right)	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	74 to 74	
Mannings n	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Relative Elevation (ft-msl)	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9	102.9
Station (ft)	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0
Flow Area (sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetted Perimeter (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Topwidth (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* Note: All input data are displayed in boxed areas.

1 Flow rates and velocities are based on Mannings equation.
2 Weighted Mannings n is the product of the Mannings n and wetted perimeter for each cross section segment divided by the total wetted perimeter for a specific flow depth.
3 Critical depth is based on [Q2/g = A3/Topwidth], where A = topwidth x critical depth.
4 Maximum elevation evaluated for critical depth. Critical depth is not considered applicable, using equation (see note 3), when flow depth exceeds overbank elevation.

11.0 SEDIMENT TRANSPORT AND ENLARGEMENT RATIO

Purpose

The calculation of sediment transport and the channel enlargement ratio on a like reach basis will provide an estimate of the future channel size and total sediment load to the stream from bank erosion.

Approach

The estimation of the enlargement ratio $\Delta(R_E)$ is a useful parameter for the establishment of planning priorities. For example, a low value of $\Delta(R_E)$ for one channel reach or system in comparison to another implies that the reach with the lower value would receive a lower priority for remediation, all other factors being equal. This approach, however, does not address factors such as the size of the channel, the depth of incision, or the potential for impute on environmental attributes. Consequently, a more powerful planning tool is suggested based on the use of parametrics describing the mode of enlargement and the sediment yield potential. Mode of enlargement refers to valley formation, widening or degradation processes. Of these processes, valley formation represents the greatest possible impact on the fluvial system because it involves the re-construction of the entire valley system at a lower elevation. The process of widening represents the next worst impact scenario because it involves planimetric adjustment of the active channel with implications of adjacent land uses. The process of degradation without an associated increase in channel width is the least impact scenario because it tends to be limited to RC channels and the rate of geomorphic activity is relatively low. The mode of enlargement is incorporated into the channel classification scheme as summarized in Table 11.1 (see Section 8.0 for a description of response scenarios).

Table 11.1. Mode of Channel Enlargement and Channel Type

Mode of Enlargement	Channel Type	Relative Potential For Impact
Valley Formation	Alluvial	High
Widening	Rock Bed	Medium
Degradation	Rock Controlled	Low[1]

1. Assumes increase in bank height does not compromise geotechnical criteria for stability.

Sediment yield potential can be estimated as a function of $\Delta(R_E)$ and bank height along the reach of interest. This requires that the anticipated enlargement be proportioned between banks. One possible method is as outlined in Table 11.2.

A suggested equation for the estimation of sediment yield is as follows:

Q_S = Length (feet)x (Change in channel area) 11.1

The change in channel width and depth are represented by ΔW_{BFL} and ΔD_{BFL} which are determined on a case-by-case basis using the procedure outlined in Table 11.2, D_{BNK} is the height of the bank at a distance ΔW_{BFL} from the original bank position, and the subscript BFL refers to the bankfull stage. The process does not consider geotechnical failures which may occur from loss of channel bank material and steeper slopes.

Table 11.2. Guidelines for Proportioning $\Delta(R_E)$ Between Left and Right Channel Banks (Not used in the watershed erosion assessments since only one cross section used per like reach)

Resistance To Scour	Left Bank (a_{LFT})	Right Bank (a_{RHT})
$(SCORE_{TOE})_{LFT} \approx (SCORE_{TOE})_{RHT}$	0.5	0.5
$(SCORE_{TOE})_{LFT} < (SCORE_{TOE})_{RHT}$	0.75	0.25
$(SCORE_{TOE})_{LFT} > (SCORE_{TOE})_{RHT}$	0.25	0.75
$(SCORE_{TOE})_{LFT} << (SCORE_{TOE})_{RHT}$	1.0	0.0
$(SCORE_{TOE})_{LFT} >> (SCORE_{TOE})_{RHT}$	0.0	1.0

Output

Data from this task will be presented on a reach basis and appear in a table similar to the following table.

TABLE 7-1
ENLARGEMENT POTENTIAL
AND SEDIMENT TRANSPORT

WATERSHED ID	FIRST LEVEL TRIB.	SECOND LEVEL TRIB.	REACH NUMBER	REACH LOCATION	STREAM TYPE	CURRENT CONDITION	REACH LENGTH (feet)	EXISTING LAND USE, CURRENT R_E	EXISTING LAND USE, ULTIMATE R_E	FUTURE LAND USE, ULTIMATE R_E	FUT ULT R_E / EXT CUR R_E (sq. feet)	SEDIMENT YIELD* (tons)	SEDIMENT TONS / LINEAR FOOT (tons / L.F.)
	Fort Branch												
FOR	000	000	01	From confluence with Boggy Creek to MKT Railroad.	Alluvial	In Adjustment	600	4.7	5.0	7.0	1.49	2209	3.68
FOR	000	000	02	From MKT Railroad to Webberville Rd.	Rock Bed	In Adjustment	9,220	2.7	2.9	3.5	1.28	32269	3.50
FOR	000	000	03	From Webberville Rd. to Springdale Rd.	Alluvial	In Adjustment	4,580	5.9	6.3	6.9	1.17	5607	1.22
FOR	000	000	04	From Springdale Rd. to Manor Rd.	Alluvial	In Adjustment	5,560	7.3	7.8	7.9	1.08	1008	0.18
FOR	000	000	05	From Manor Rd. to Tributary at Westminster Dr. and Waterbrook Dr.	Alluvial	In Adjustment	2,500	7.5	8.0	8.2	1.09	1198	0.48
FOR	000	000	06	From Tributary at Westminster Dr. and Waterbrook Dr. to Rogge Ln.	Structural	Stable	1,750	2.9	3.1	3.2	1.10	0	0.00
FOR	000	000	07	From Rogge Ln. to150 ft. D'S Berkman Dr.	Alluvial	In Transition (Stressed)	1,550	8.6	9.2	9.8	1.13	446	0.29
FOR	000	000	08	From 150 ft. D/S Berkman Dr. to 550 ft. D/S Glencrest Dr.	Structural	In Transition (Stressed)	2,200	3.4	3.6	3.8	1.12	114	0.05
FOR	000	000	09	From 550 ft. D/S Glencrest Dr. to U.S. 290	Alluvial	In Transition (Stressed)	1,350	9.5	10.0	10.1	1.06	123	0.09
				Tributary									
FOR	T01	000	01	From confluence with Fort Branch to Wheless Ln.	Alluvial	In Transition (Stressed)	3,850	3.9	4.1	5.5	1.43	1877	0.49

* Based on one (1) cross section per reach.

12.0 EROSION HAZARD INDICATOR

An erosion hazard indicator is a bracket shown on both sides of the channel at the location of the field cross section to show the potential for the estimated increase in channel to width. This bracket which appears on the mapping in the watershed erosion assessments will assist report users in determining the effect of channel erosion to structures, parks, woodlands, and trails. A bracket is provided if the increase in top width is greater than 10 feet, since increases less than 10 feet are not discernible at a scale of 1 inch equals 200 feet.

The bracket is based upon the computed enlargement ratio for the future watershed development and corresponding ultimate channel adjustment. This increase in top width is an average and does not address localized erosion rates at meanders, ends, storm drain outfalls, etc., which can generate top width expansion bends the average estimate. This top width increase is applied at the top of bank, however, expansion of the inset channel and active channel within the floodplain channel are not shown as a top width increase. An assumption for this study is that rock outcrops such as hard limestone will effectively armor a stream bank thereby resulting in the majority of erosion occurring to the opposite stream bank.

Since the study is not using a shear stress model to determine the bank, most susceptible to erosion, the channel widening was applied equally to both channel banks, unless limestone or other hard rock was identified in the reach.

See the attached table for an example of the Erosion Hazard Indicator computations and resulting channel top width expansion. The erosion hazard will appear on the 1" = 200' scale topographic maps shown in each report.

FIGURE 11-1
EROSION HAZARD AREA

	Fort Branch									
WATERSHED ID	FIRST LEVEL TRIB.	SECOND LEVEL TRIB.	REACH NUMBER	REACH LOCATION	STREAM TYPE	REACH LENGTH (feet)	FUT ULT R_E / EXT CUR R_E	TOTAL TOP WIDTH ENLARGEMENT (feet)	TOTAL SEDIMENT YIELD* (tons)	SEDIMENT YIELD PER LINEAR FOOT (tons / L.F.)
FOR	000	000	01	From confluence with Boggy Creek to MKT Railroad.	Alluvial	600	1.49	3.5	2209	3.68
FOR	000	000	02	From MKT Railroad to Webberville Rd.	Rock Bed	9,220	1.28	4	32269	3.50
FOR	000	000	03	From Webberville Rd. to Springdale Rd.	Alluvial	4,580	1.17	0	5607	1.22
FOR	000	000	04	From Springdale Rd. to Manor Rd.	Rock Bed	5,560	1.08	0	1008	0.18
FOR	000	000	05	From Manor Rd. to Tributary at Westminster Dr. and Waterbrook Dr.	Alluvial	2,500	1.09	1	1198	0.48
FOR	000	000	06	From Tributary at Westminster Dr. and Waterbrook Dr. to Rogge Ln.	Structural	1,750	1.10	0	0	0.00
FOR	000	000	07	From Rogge Ln. to150 ft. D'S Berkman Dr.	Alluvial	1,550	1.13	1.5	446	0.29
FOR	000	000	08	From 150 ft. D/S Berkman Dr. to 550 ft. D/S Glencrest Dr.	Structural	2,200	1.12	0	114	0.05
FOR	000	000	09	From 550 ft. D/S Glencrest Dr. to U.S. 290	Alluvial	1,350	1.06	0	123	0.09
				Tributary						
FOR	T01	000	01	From confluence with Fort Branch to Wheless Ln.	Alluvial	3,850	1.43	0	1877	0.49

RAYMOND CHAN AND ASSOCIATES, INC.

* From enlargement process based on one (1) cross section per reach.

FORTBR11.XLS

13.0 KNICK POINT MANAGEMENT

Purpose

Knick points will be identified in the stream inventory phase of each watershed assessment to assist in the analysis of reach stability and the potential for future erosion problems. The migration of knick points indicates headcutting and the potential downcutting of the stream channel bed resulting in possible bank failures, channel widening, increased sediment load, and their effects on structures and features located near channel banks.

Background

13.1 INTRODUCTION

Knickpoints represent an abrupt discontinuity in the longitudinal profile of the channel bed. These discontinuities may be associated with the intersection of relatively horizontal bedding planes by the oblique slope of the longitudinal profile of the channel bed and natural differences in the prevailing erosion rates of the inter-bedded materials, e.g. massively bedded limestone inter-bedded with thinly bedded, fractured shale. The typical form is a step like feature comprised of a more resistant cap rock underlain by a weaker material. Attack of the underlying material by ice plucking, cavitation pressure, pore water pressure, and expansion-contraction forces results in the retreat of this material. The overlying material assumes an extended position and becomes more susceptible to failure from tension cracks and other failure mechanisms. Upon failure of the cap rock the entire process is repeated but at a position upstream from the starting point. Hence the upstream migration of the knickpoint.

Knickpoints may also be due to anthropogenic influences such as erosion of a scour hole created by the velocity jet associated with discharge from a storm sewer outlet. In this instance the knickpoint may be created by a breach in the armor layer within the receiving channel. If the underlying substratum is relatively weak, a scour hole will form. The armor functions as the cap rock which is undermined by erosion of the weaker underlying materials.

Regardless of their origin, these discontinuities can migrate in both the upstream and downstream directions. Depending upon channel type, they can result in significant alterations in channel form. Knick points of 0.75 m (2 ft) to 2.5 m (8.2 ft) are common in small urban streams resulting in the entrenchment and widening of the channel as they propagate from the point of initiation. The rate of migration of these features is also highly variable. Evidence collected from the monitoring of knickpoint migration in Morningside Creek in Markham, Ontario, indicates that these features can migrate over tens to hundreds of meters per year in some circumstances. In this case, the armor layer was breached resulting in exposure of a thin substratum of intact, compacted clayey till over a thick unit of coarse sand. Erosion through the clayey material took several years, during which time knickpoint migration could be measures in meters per year. However, erosion into the sand layer resulted in the accelerated migration of these features at rates of tens to hundreds of meters per year. The propagation of these features also resulted in rapid downcutting and valley formation within the alluvial system. In contrast, monitoring of knickpoints formed in inter-bedded, shale-limestone materials in Shardon Creek, Mississauga, Ontario suggest that these features (maximum height 1 m (3.3 ft)), are migrating at rates measured in a centimeters per year. At these rates the knick point would require over 500 years to migrate a distance of 100 m (330 ft). However, geotechnical constraints imposed by adjacent steep banks and homes along the valley top-of-bank, make even this slower rate of retreat unacceptable. Consequently, mitigative measures are required.

Numerous knick points were observed in the streams surveyed in the Austin area. Although all of these features can be considered agents of significant morphological change, the rates of migration and severity of impact on structures and habitat features varied widely. Consequently, a program for the management of these features would require a case-by-case evaluation of the need for and priority of mitigation measures.

13.2 MITIGATION MEASURES

Knickpoints are controlled naturally through burial by sediments or by the occurrence of outcrops of massively bedded, resistant bedrock materials. The rock outcrops simply interrupt the horizontal bedding planes of alternating hard and soft materials. While burial of the knickpoint serves to protect the materials from exposure to weathering processes. Both of these natural controls form models for the mitigation of knickpoint migration.

Burial of the knickpoint is achieved by replacing the abrupt drop associated with the knickpoint with a more gradual decline in the form of a constructed riffle element. Where armor already exists on the bed, design of the riffle section is relatively straight forward. The dimensions of the riffle are modeled after a 'real world' prototype and the ends of the riffle are integrated into the existing armor layer. This is done in a manner that minimizes any hydraulic discontinuity that may cause the de-stabilization of the adjoining reaches. The hydraulic losses through the riffle section are designed to be equivalent to those losses created by the knickpoint itself.

Where the bed material is composed of exposed bedrock the transition into and out of the riffle is more complex. To prevent the armor layer within the constructed riffle section from being swept away, concrete or limestone block sills, which are keyed into the bed, may used at the upstream and downstream ends of the riffle. These sills are buried under the riffle material and consequently they are hidden from view. The upstream sill is constructed to an elevation that slightly exceeds the elevation of the bed. This lip serves to trap bedload from upstream reaches. The upstream propagation of these sediments results in the armoring of the bed with indigenous materials and a smooth transition into the constructed riffle section.

The above method works well for lower gradient channels with relatively small knickpoints. The actual height of the knickpoint which can be managed in this way is determined by the dimensions of naturally occurring riffles under similar hydraulic and geomorphic conditions. Where the height of the knickpoint exceeds this critical point or the stream channel gradient is that of a step-pool type morphology, the rock outcrop model is suggested. This technique involves stabilization of the face of the knickpoint and the creation of a plunge pool to dissipate flow energy. Stabilization of the face of the knickpoint may be achieved using a concrete sill keyed into the bed immediately upstream of massive armor stone block. The block is placed in a semi-random manner to achieve a natural appearance. These blocks also continue downstream forming a depression of imbricated boulders much like the shape of a bowl. The downstream lip of the bowl may be formed by limestone block upstream of a concrete sill which is keyed into the bedrock. Once again the sill is buried under the armor stone and is not visible. The downstream lip of the bowl is at the elevation of the existing bed to avoid transition problems and erosion of the existing channel. The bowl is designed to provide for the dissipation of flow energy equivalent to losses achieved through the original knickpoint.

These techniques can effectively stabilize the knickpoints in a relatively cost effect manner with low maintenance and high aesthetic value. Where continuity between reaches is required for fish passage these techniques can be designed, as with natural riffle and step-pool systems to allow for fish migration.

Approach

During the stream inventory, the field team will identify all knick points greater than one foot in height. Knick points can be artificial such as wastewater lines and bridges (which can act as grade control structures) or can be the natural process of the stream bed lowering in an upstream direction. The field team will identify the following aspects at each knick point:

Location,

Height,

Channel substrate and substratum if necessary, and

Features that may influence the movement of the knick point.

In the office, engineering staff will measure the distance between the knick point and a structure that can act as a grade control and inhibit the migration of the knick point. Such structures as concrete culverts, encased wastewater lines, and rock outcroppings can limit knick point migration and prevent the upstream portion of a reach from experiencing downcutting.

Output

A table (see following) will be provided in each watershed assessment similar to present the above data on knick points. Knick points will be shown on the 1 inch equals 200 feet topographic mapping. The knick points should be considered in overall reach stability, erosion control projects, and stream restoration projects.

TABLE 8-1
KNICK POINT SUMMARY

	Fort Branch						
REACH NO.	KNICK PT. NO.	LOCATION	STATION	HEIGHT	FEATURE	SUBSTRATE	DISTANCE TO GRADE CONTROL
			(feet)	(feet)			(feet)
2	1	100 ft. D/S Webberville Rd.	9720	3.0	Sanitary sewer Line	Bedrock	0
3	2	100 ft. D/S Heflin Ln.	10920	3.0	Sanitary sewer Line	s/gr	0
4	3	2350 ft. D/S Old Manor Rd.	17660	5 to 6	Concrete Apron	Bedrock	0
4	4	300 ft. D/S Old Manor Rd.	19660	1.3	Concrete Apron	Concrete	0
4	5	50 ft. D/S Old Manor Rd.	19910	2.0	Concrete Apron	Concrete	0
5	6	300 ft. D/S Confluence of Tributary	22160	2.0	Sanitary Sewer Line	gr/co	0

14.0 MEANDER MIGRATION AND EXCESSIVE BENDS

Purpose

This activity will be performed to assess the migration potential of meanders in alluvial systems within a sinuous reach and how meander migration may affect structures near stream banks. Also, channel bends of 60 degrees or larger will be identified since most of the Drainage Utility's completed erosion projects were located on the outside of channel bends.

Approach

The active channel in meandering streams shift in position through time as a natural means of transporting sediment through the channel network. In this regard the active channel can be viewed as a conveyor belt moving sediment down slope through the downstream translation of the meander form. This is achieved through erosion of the outer (concave) meander bank and the concomitant deposition on the inside (convex) meander bank. The majority of this erosion occurs in the downstream third of the meander bend. Consequently, meanders tend to move in both a lateral (right angles to the longitudinal (down slope) direction of the floodplain valley) and down slope direction. The rate of migration of meanders has been described by Hickin and Nanson (1984) as a function of the form,

$$M = f(\Omega, \tau_b, D_{BNK}, r, W_{BFL})$$

in which, 'M' is the rate of channel migration, Ω represents stream power (the ability of the stream to do work, i.e. erode its boundary), τ_b is the strength of the basal stratigraphic unit (the ability of the bank to resist erosion), D_{BNK} is the height of the bank, 'r' is the radius of curvature of the meander bend and W_{BFL} is the width of the channel at bankfull stage. Using dimensional analysis they developed a relation of the form,

$$M = K(\Omega\, W_{BFL}) / (\nu\, \tau_b\, D_{BNK})$$

wherein K is a coefficient.

Hickin and Nanson (1984) concluded that 'M' is strongly controlled by the radius of curvature of the meander bend such that the rate of meander migration was at a maximum when $2.0 < r/W_{BFL} < 3.0$. For tight meander bends ($r/W_{BFL} < 2.0$) and in the domain $r/W_{BFL} > 3.0$, the rate of meander migration declines.

The strength of the basal unit of the channel bank material was also significant in that as grain size declines from cobbles to fine sand, τ_b decreases to a minimum. As the amount of material in the silt-clay size range increases, τ_b increases to a maximum value. It should be cautioned, however, that channel sensitivity to scour is very site specific.

The relationship between M and Ω is influenced by τ_b, however, M generally increases in a non-linear manner with increasing stream power per unit width of stream. Streams having a relatively high erosive potential tend to have high migration rates where τ_b is low. Hickin and Nanson (1984) reported that the relationship between migration rate and stream width was difficult to isolate because of the confounding effect of the intermittent nature of channel migration and the complex relationship between migration and channel curvature.

Although the Hickin and Nanson (1984) relation was developed for rivers in the prairies and the role of riparian vegetation was not directly addressed, the relation is physically based and it provides a useful means for assessment of the potential for meander migration in alluvial channels in the Austin area.

Output

Each like reach in an alluvial channel type will be measured to determine reach sinuosity. If the sinuosity exceeds 1.2 ($L_{channel} / L_{valley}$), then a reach is of a sinuous nature (Rosgen, 1996). Reaches with a sinuosity greater than 1.2 will be examined by applying the relationship $2.0 < r/W_{BFL} < 3.0$ to each meander bend. If the meander does not satisfy this criteria, then the meander bend is assumed to migrate at a normal rate. However, if the meander does fall within the range of the above stated relationship, then the meander will be targeted as having the potential to migrate at a rapid rate. This will be identified in the report and considered as part of the recommendations for managing channel erosion. Considerations will include creating a longer radius of curvature to reduce the rate of migration. Excessive bend and meander migration data will be provided in tabular format as per the attached tables.

TABLE 9-1

MEANDER MIGRATION SUMMARY
ALLUVIAL REACHES ONLY

		Fort Branch								
MEANDER NO.	**REACH NO.**	**LOCATION**	**STATION ID**	**EROSION PROBLEM**	**AFFECTED RESOURCE**	**REACH SINUOSITY**	**RADIUS**	**BANKFULL WIDTH**	**R / Wbkfl**	**2 < R / Wbkfl < 3 ?**
							(feet)	**(feet)**		
1	1	500 ft. D/S M.K.T. Railroad Bridge	100	None	N.A.	1.09	105	40	2.6	yes
2	3	900 ft U/S Webberville Rd.	10700	None	N.A.	1.12	100	40	2.5	yes
3	3	600 ft U/S Heflin Lane	13400	None	N.A.	1.12	85	35	2.4	yes

TABLE 9-2

EXCESSIVE BEND SUMMARY

		Fort Branch					
BEND NO.	REACH NO.	LOCATION	STATION ID	CHANNEL TYPE	EROSION PROBLEM	AFFECTED RESOURCE	BEND
							(degrees)
1	2	D/S M.K.T. Railroad Bridge	600	Alluvial	Type 3	RR Bridge	65°
2	2	600 FT. U/S M.K.T. Railroad Bridge	1200	Rock Bed	Type 2	Tree	90°
3	2	1200 FT. U/S M.K.T. Railroad Bridge	1800	Rock Bed	Type 2	Tree	90°
4	2	1400 FT. U/S M.K.T. Railroad Bridge	2000	Rock Bed	None	N.A.	90°
5	2	At Tura Lane (extended)	2200	Rock Bed	Type 2	Tree	110°
6	2	At Tura Lane (extended)	2350	Rock Bed	Type 3	Tree	70°
7	2	At the S. end of Eleanor Ave. Near Harold Court	3800	Rock Bed	Type 2	Tree	180°
8	2	At the S. end of Eleanor Ave. Near Harold Court	4000	Rock Bed	Type 3	House	180°
9	2	Ledesna Drive and Christie Drive (extended)	4500	Rock Bed	None.	N.A.	90°
10	2	Fort Branch Street at Hudson Street (extended)	5800	Rock Bed	Type 3	Fence/ yard	180°
11	2	Lott Ave. at Delores Ave. (extended)	5950	Rock Bed	None.	N.A.	110°
12	2	300ft. D/S Webberville Rd.	9520	Rock Bed	Type 3	House/Tree	70°
13	3	100 ft U/S Webberville Rd.	9900	Alluvial	None.	N.A.	90°
14	3	200 ft. D/S Helfin Lane	10900	Alluvial	Type 3	Building	60°
15	3	250 ft D/S MLK Blvd.	11800	Alluvial	Type 2	Tree	110°
16	3	1100 ft. D/S Springdale Rd.	13200	Alluvial	None.	N.A.	100°
17	4	200 ft U/S Springdale Rd.	14600	Rock Bed	Type 3	Tree	90°
18	4	600 ft. D/S Pecan Springs Rd.	15500	Rock Bed	Type 3	Tree	90°
19	4	250 ft. D/S Pecan Springs Rd.	15850	Rock Bed	None	N.A.	120°
20	4	1000 ft. U/S Pecan Springs Rd.	17100	Rock Bed	None	N.A.	90°
21	4	1200 ft. U/S Pecan Springs Rd.	17300	Rock Bed	None	N.A.	180°
22	6	200 ft. D/S Westminster Dr.	22500	Structural	None	N.A.	90°

15.0 PRIORITIZATION OF EROSION PROBLEMS AND REACHES

Purpose

In order to develop and implement a sound management plan, a decision making protocol was developed to permit a thorough and systematic assessment of the erosion problems within a like reach. This system developed by the City of Austin Drainage Utility staff was utilized to rank like reaches to compare their relative erosion problems. The use of this tool allows the identification of the most problematic reaches within a watershed or the City. The City can then initiate the desired erosion management process by selecting the appropriate activities to mitigate channel erosion within the desired reach.

See the following summary sheets for the prioritization system flow chart.

STREAM EROSION PRIORITIZATION SYSTEM OVERVIEW

- Problem SCORE (Geomorphic Reach) = $\Sigma(W_1$*Type 1 SCORE, W_2*Type 2 SCORE, W_3*Type 3 SCORE)
- Weights (i.e., W_1, W_2, and W_3) are assigned to each prioritization factor.
- Type 1 SCORE = f(Resource Value, Current Problem Severity, Future Problem Severity)
- Type 2 SCORE = f(Resource Value, Current Problem Severity, Future Problem Severity)
- Type 3 SCORE = f(Resource Value, Problem Severity)

Definitions

Type 1 - Roads, houses, and buildings currently threatened

Type 2 Sites - Other resources currently threatened

Type 3 - Resources not currently threatened but may be threatened in future

Geomorphic Reach - as defined by consultant based on channel geomorphology. Channels will be classified as either Alluvial, Rock Bed, or Rock Controlled.

SEQUENCE FOR CALCULATING PRIORITY PROBLEM AREAS FOR STREAM EROSION

Step 1.
Evaluate Each "Excessive" Meander Site - Calculate Problem SCORE. Compile results for each Geomorphic Reach.

Step 2.
Evaluate Each Knickpoint - Calculate Problem SCORE. Compile results for each Geomorphic Reach.

Step 3.
Evaluate Each Geomorphic Reach - Calculate Problem SCORE

Step 4.
Evaluate Each Type 1 Property Protection Site. Calculate Problem SCORE for each. Compile results to calculate Type 1 Problem SCORE for each Geomorphic Reach.

Step 5.
Evaluate Each Type 2 Property Protection Site, with exception of Hike and Bike Trails, Parkland, and Priority Woodlands. Calculate Problem SCORE for each. Compile results for each Geomorphic Reach.

Step 6.
Evaluate remaining Type 2 Property Protection Sites, i.e., Hike and Bike Trails, Parkland, and Priority Woodlands. Calculate Problem SCORE for each. Compile results for each Geomorphic Reach.

Step 7.
Calculate Type 2 Problem SCORE for each Geomorphic Reach (combine Steps 3 and 4)

Step 8.
Evaluate Each Type 3 Property Protection Site, with exception of Hike and Bike Trails, Parkland, and Priority Woodlands. Calculate Problem SCORE for each. Compile results for each Geomorphic Reach.

Step 9.
Evaluate remaining Type 3 Property Protection Sites, i.e., Hike and Bike Trails, Parkland, and Priority Woodlands. Calculate Problem SCORE for each. Compile results for each Geomorphic Reach.

Step 10.
Calculate Type 3 Problem SCORE for each Geomorphic Reach (combine Steps 3 and 4)

Step 11.
Calculate Total Problem SCORE for each Geomorphic Reach by combining above steps.

FORT BRANCH
OVERVIEW

The stream erosion prioritization system is based on the following goal and objectives:

GOAL: Protect property from damage resulting from stream erosion in the most cost-effective manner which maximizes benefits to water quality and flood control activities.

OBJECTIVES

No.	Importance	Description
1	HIGHEST	Repair all Type 1 problems by 2040.
2	HIGH	Repair all Type 2 problems by 2040.
3	HIGH	Prevent Type 3 problems from occurring.
4	HIGH	Achieve stable stream systems in all creeks by 2040.
5	HIGH	Allow no net increase in instream erosion potential in all creeks by 2040.

STRATEGIES:

1. Implement in-stream stabilization projects, utilizing bio-engineering approaches when possible.
2. Control watershed hydrology.
3. Eliminate or minimize the impacts of in-stream obstacles, direct discharges, and other physical structures which cause erosion.
4. Minimize the impacts of construction and maintenance activities on stream stability and properties.
5. Create or maintain vegetative buffers along stream corridors.
6. Remove structures currently located within erosion hazard zones.
7. Prevent structures from being constructed within erosion hazard zones.

FORT BRANCH
FINAL_MATX

STREAM EROSION PROBLEM AREA PRIORITIZATION SYSTEM

Problem SCORE = (W1*Type1_SCORE) +(W2*Type2_SCORE) + (W3* Type3_SCORE)

Scoring Factors and Weights		
Factor	Weight	
Type 1	0.50	INPUT REQUIRED
Type 2	0.30	IN
Type 3	0.20	HIGHLIGHTED CELLS
Total	1.00	

NOTE: ADD ENDPT OF LAST REACH IN NEXT ROW

Geomorphic Reach ID	Reach ID	Station_ID (D/S Endpoint)	Type 1 Sites Cumulative Reach SCORE	Type 1 Sites Rank SCORE	Type 2 Sites Cumulative Reach SCORE	Type 2 Sites Rank SCORE	Type 3 Sites Cumulative Reach SCORE	Type 3 Sites Rank SCORE	Total SCORE	Rank SCORE	Rank
FOR-1	FOR 000 000 000000	0	0.0	0.0	62.6	13.7	37.3	21.4	8.4	12.8	5
FOR-2	FOR 000 000 000600	600	0.0	0.0	458.2	100.0	174.1	100.0	50.0	76.6	2
FOR-3	FOR 000 000 009820	9820	0.0	0.0	250.2	54.6	77.5	44.5	25.3	38.7	3
FOR-4	FOR 000 000 014400	14400	0.0	0.0	41.9	9.1	33.1	19.0	6.5	10.0	6
FOR-5	FOR 000 000 019960	19960	54.9	100.0	208.9	45.6	14.1	8.1	65.3	100.0	1
FOR-6	FOR 000 000 022460	22460	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10
FOR-7	FOR 000 000 024210	24210	0.0	0.0	0.0	0.0	9.3	5.3	1.1	1.6	8
FOR-8	FOR 000 000 025760	25760	0.0	0.0	0.0	0.0	5.5	3.2	0.6	1.0	9
FOR-9	FOR 000 000 027960	27960	0.0	0.0	42.3	9.2	14.1	8.1	4.4	6.7	7
		29310									
FOR-T1-1	FOR T01 000 000000	0	0.0	0.0	118.2	25.8	28.6	16.4	11.0	16.9	4
		3850									
								MAX	65.3		

FORT BRANCH
RESOURCE_VALS

Proposed Final Resource Values for Property Protection - Flooding and Erosion

Resource	Code	Resource Value	Notes
Major Road	MAJROAD	100	
Minor Road	MINROAD	75	
Public Recreational Amenity	PRA	50	Includes swimming pools, tennis courts, playscapes, hike and bike trails, and other tangible assets
Swimming Pool	POOL	50	
Tennis Court	TENNIS	50	
Playscape	PLAY	50	
Hike and Bike Trail		50	
Public Parkland >=500 LF		50	Not including amenities
Public Parkland <500 LF		40	Not including amenities
Priority Woodland (public)		60	
Priority Woodland (private)		35	
House	HOUSE	90	
Building	BUILDING	90	
Mobile Home	MOBILE	90	
Fixed Storage Building	FSB	50	
Retaining Wall	WALL	45	
Protected Tree	TREE	45	
Manhole	MANHOLE	45	
Railroad Bridge	RR BRIDGE	75	
Pedestrian Bridge	PEDBRIDGE	50	
Utility Line	UTILITY	45	
Power Pole	POLE	45	
Fence	FENCE	30	
Pipeline	PIPE	45	
Yard (major loss)	YARD	35	

16.0 STREAM MANAGEMENT RECOMMENDATIONS

Purpose

In each watershed assessment, recommendations will be developed for erosion prone structures, problematic reaches, and stream restoration sites based on the study findings. The recommendations will be based on the geomorphic analysis (enlargement ratio, impervious cover, etc.), knick point migration, meander movement, erosion problems, and restoration opportunities to assist the City in implementing the appropriate stream management solution. Opportunities to combine erosion improvements with flood and water quality management strategies should be investigated whenever possible.

Approach

16.1 INTRODUCTION

Hasen (1996) proposed a stream classification system based on *Type* and *Method* of stabilization for river restoration programs. This method first identifies the disturbance in the causative factors controlling channel form then links the temporal and spatial scale of the disturbance to the scale of mitigation works required to restore the channel to the target state. The scale of the restoration works and an understanding of the morphology of the channel and dominant processes operating within the channel system are then employed in the selection and design of the mitigation works. This approach provides a watershed scale perspective on the development of restoration programs and consequently, it provides a sound basis for the development of comprehensive, coordinated riparian management plans.

In Hasen's (1996) approach the term 'restoration' refers to 'habitat enhancement' programs which are designed to increase habitat and aesthetic value within the project reach(es) to a desired or target condition but do not necessarily return the channel to an historic form. The *Type* of restoration program refers to the purpose and spatial scale of the works and *Method* identifies the actual mitigation approach to be adopted. While the magnitude, spatial scale and temporal characteristics of the factors causing channel instability or the deviation of channel form from the target form are implicit in this approach, they have been explicitly identified in the modified approach presented below. Also inherent in Hasen's (1996) method is the assumption that a desired or target habitat/channel morphology can be identified. Similarly, the approach adopted here assumes that target conditions are established either prior to or as an initial phase of the restoration project. Consequently, the development of restoration goals and objectives are not addressed in this discussion.

While channel geomorphology and habitat features are inextricably linked, for the sake of brevity, the emphasis of this Section will be on the stabilization component of the restoration program. It should be noted, however, that channel works can be designed to meet habitat function when this aspect is *identified* as a significant component of the restoration program. A discussion of the link between morphologic features and habitat function is provided by Imholf et al., (1996) and others.

16.2 DEFINITION OF CHANNEL TYPES-METHODS

As with any classification system which attempts to divide a continuum of complex natural phenomena into discrete groupings, this method will have overlaps. However, in general projects could be classified as being of one of three *Types* as described below:

Classification Program by *Type:*

Type 1:	Rehabilitation of Water Course Reaches;
Type 2:	Restoration of Continuity Between Water Course Reaches; and,
Type 3:	Rehabilitation of River Valleys.

16.2.1 *Type* 1 Restoration Programs (localized)

Type 1 restoration programs involved specific units or lengths of channel[4] wherein the stabilization works for these units of channel could be undertaken in isolation of upstream or downstream channel morphology (Table 16.1). In these instances the cause of channel

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1. An element is a length of channel defined by a planimetric feature such as a riffle, pool or run.
2. A site is a length of channel which is composed of part or all of one or more elements but is less than the length of a segment.
3. A segment is a length of channel encompassing 2 meander wavelengths in a meandering stream or a length of channel equivalent to 20 bankfull channel widths in a run.
4. A reach refers to a length of channel with common morphologic characteristics such that any segment within the reach would have parameter values describing the planimetric and hydraulic geometry form within the expected range of variance.

Table 16.1. ***Type* 1 Classification of Restoration Works**

TYPE 1: SITE LEVEL REHABILITATION OF WATERCOURSE	
Floodplain Management	Terraced cross-section profile to reconnect channel to its floodplain Culvert enlargement or replacement with open channel to reduce concentration of flood flows within the channel Backwater ponds and spillways Water level management
Channel Hydraulic Geometry Modifications	Culvert replacement with open channel to enhance fish passage and habitat function Side channels Re-meandering of straightened reaches Width/depth adjustment Creation of pools/riffles Slope adjustment Energy dissipaters at storm sewer outfalls
Riparian Vegetation	Riparian planting and/or removal of riparian vegetation Creation of a buffer zone Fencing
Flow Modifications	Flow deflectors, groins, boulder placement Channel constrictors Check dams (rocky bottom raps or artificial riffle sections)
Substrate Manipulation	Addition and/or removal of artificial bed and/or bank materials Artificial shoals Sediment traps

erosion can be interpreted as local in spatial extent and the restoration works are applied over the length of the impact zone. In some cases mitigation of the cause of instability at its source is also a consideration. An example of a *Type* 1 program would be the stabilization of a scour hole and associated knick point at a storm sewer outfall or downstream of a culvert under a road crossing. Another example would be the introduction of meanders into a previously straightened reach designed in such a way as to have no net impact on downstream or upstream units

16.2.2 *TYPE* 2 RESTORATION PROGRAMS

<u>*Type* 2 restoration programs involve two or more channel units wherein the works in one unit affect or are impacted by other units</u>. (Table 16.2) In this case works can not be implemented in isolation of units located, either or both, downstream or upstream of the subject unit. For example, the removal of a dam may alter the flow and sediment regime in downstream units and the erosion of the sediment wedge behind the dam may result in the upstream migration of a knick point. Stabilization works in this case may involve: removal of the obstruction (the dam) in phases to reduce the severity of the impact on

downstream units coupled with *Type* 1 or 2 level works in the upstream and downstream units.

16.2.3 *TYPE* 3 RESTORATION PROGRAMS

Type 3 restoration programs involve watershed scale stabilization schemes (Table 16.3). An example would be a basin which has undergone or is in the process of a change in land use or land use practice wherein these changes have significantly altered the prevailing sediment and flow regimes in the watershed. Examples would include large scale logging operations, the urbanization of a watershed from previously agricultural use, and the construction of a reservoir. In these situations the proposed works can not be designed and implemented without consideration of the long term implications on channel form associated with the change in the prevailing sediment and flow regimes. In the case of urbanization, stabilization programs may include control of flows and sediment in the Production Zone through Stormwater Management (SWM) retrofit programs, SWM controls on new developments, and the implementation of *Type* 1, 2 and 3 level *Methods*.

16.3 APPLICATION OF THE CLASSIFICATION SYSTEM

In order to apply this classification scheme the factors causing instability within the channel and the geomorphic response must first be identified and characterized. The *Type* and *Method* of restoration program can then be ascertained along with the level of effort required to stabilize the channel. To facilitate this process an eleven step protocol was proposed as a guide to assessment of the fluvial system, characterization of the restoration project and design of the restoration program. These Steps are outlined in Table 16.4 along with possible methods of analysis and the desired output from each Step.

Table 16. 2. ***Type*** **2 Classification of Restoration Works**

TYPE 2: RESTORATION OF CONTINUITY BETWEEN WATERCOURSE UNITS	
Floodplain Management	See *Type* 1 level methods
Channel Modification	Obstruction replaced by a riffle Bypass riffle established at preserved obstruction Obstruction replaced by meandering channel Obstruction preserved and bypassed by meandering channel Fish passageway established or removed Create a riverine wetland all *Type* 1 level methods
Riparian Vegetation	See *Type* 1 level methods
Flow Modification	On-line/off-line storage facility created in the floodplain to augment baseflow and/or to modify high flows Baseflow augmented through pumping all *Type* 1 level methods
Substrate Manipulation	See *Type* 1 level methods

Table 16.3. *Type* 3 Classification of Restoration Works

TYPE 3: REHABILITATION OF CHANNEL AT WATERSHED SCALE	
Floodplain Management	Removal of development from within the floodplain Restoration of the floodplain through excavation of fill Terracing floodplain to reconnect floodplain and channel Terminate storm drains in wet meadows or wetlands created in the floodplain to trap selected water quality constituents and raise the water table Reforestation program Management of stream aggregate mining activities all *Type* 1 and 2 level methods
Channel Modifications	Raising the channel bed to reconnect channel and floodplain Create a riverine wetland all *Type* 1 and 2 level methods
Riparian Vegetation	See *Type* 1 level methods
Flow Modification	Create off-line ponds in the Production Zone to augment baseflow, control runoff rate during high flows and trap sediments Apply source controls to reduce any increase in runoff and sediment mass created in association with anthropogenic activities in the Production zone Establish a dam to control flood frequency and duration and augment baseflows Use meadow/wetland flow trickling to augment baseflow All *Type* 1 and 2 level methods
Substrate Manipulation	See *Type* 1 level methods

Table 16.4. Eleven Step Design Protocol

STEP	ANALYTICAL APPROACH	OUTPUT
1. Is the channel within the expected range of variance?	i) desk top analysis of historic land use and land use practices ii) review of topographic, geologic, soils mapping iii) review of previous studies iv) analysis of historic aerial photography, engineering drawings, flow/climate/lake level records, well logs, etc. v) determination of 'like' morphologic reaches & stream continuity for fish passage vi) constraint mapping vii) synoptic field survey using geomorphic (see Table 5) and biotic Rapid Assessment techniques viii) stream classification ix) comparison of parameters describing channel planimetric and cross-sectional form to a regional data base of 'like' stream types or regionally derived hydraulic geometry relations x) qualitative assessment of the nature/scope of the perceived problem	The channel is: a) within the expected range of variance b) outside of the expected range of variance. If (a) is true proceed to (4), otherwise proceed to (2).
2. What are the principle factors responsible for the alteration in channel form?	I) identify the causative factor(s) ii) determine the magnitude and spatial/temporal characteristics of the causative factor(s)	Characterization of the problem under current land use/land use practices
3. What was the historical channel morphology?	I) use geomorphic models (hydraulic geometry relations, empirical formulas i.e. enlargement ratio as a function of percent impervious cover (calibrated to regional data or historic observations of channel form), or conceptual models) to hindcast; and/or ii) use a reference section	Baseline channel form

STEP	ANALYTICAL APPROACH	PRODUCT
4. What additional perturbations in the fluvial system are anticipated?	I) identify the nature and temporal-spatial characteristics of the perturbation(s) based on an assessment of future land use plans, channel management plans, flow/sediment regulations, dam operating protocols, and the impact of natural phenomena such as climatic change and isostatic rebound, etc.	Type, magnitude and probable impact of future perturbations
5. Field Program	I) geomorphic survey: hydraulic geometry; sedimentology (pebble counts on substrate in riffles and pools, particle size distribution of sediments on point bars, bank material and substratum characteristics (particle size and Atterburg Limits by stratigraphic unit); longitudinal profile; cross-section profile; pool-riffle dimensions; planimetric form (meander wavelength, amplitude, radius of curvature); floodplain dimensions; observations of aggradation and degradation; grade controls (knick points, bed rock outcrops, grade control structures) ii) biotic survey: not described in this paper iii) water quality survey: temperature for determination of groundwater influx; other parameters are not described in this paper iv) hydrologic survey: flow gauging station; rating curves; precipitation-temperature gauges v) groundwater survey: occurrence of seepage faces-springs; water temperature; evidence of soil piping vi) soils survey: boreholes; bank stratigraphy vii) hydraulic survey: 2-D flow field measurements at mid and bankfull flow stages; longitudinal flow field at high flow; bridges; culverts, and outlets viii) utility lines ix) property boundaries	
6. How will the channel respond?	i) using conceptual geomorphic models, empirical relations, indicators and/or reference channels, determine the probable response of the channel system	Probable ultimate channel planimetric and cross-section configuration

7. Can the perturbations be controlled at source?	I) develop a suite of possible mitigative strategies including structural and non-structural measures ii) assess the effectiveness of mitigative measures using empirical or deterministic models and/or a reference channel	The need to address future perturbations into the design of the restoration project
8. Is the ultimate channel form desirable, acceptable, or not acceptable?	I) evaluation of channel attributes relative to project goals, objectives and criteria e.g. Factor-Index method of analysis	A recommendation to develop a restoration program in whole or part (proceed to next Step) or not to proceed (conclude study)

STEP	ANALYTICAL APPROACH	PRODUCT
9. Is intervention desirable, feasible and practical?	I) formulate a long list of restoration alternatives ii) develop a decision making protocol iii) undertake a screening level analysis to generate a short list of recommended alternatives iv) assess whether intervention is desirable, feasible and practical	A preferred set of feasible and practical restoration programs is developed (proceed to next Step) or terminate study
10. What is the preferred restoration program?	I) develop conceptual design sketches of the recommended alternatives ii) produce preliminary cost estimates iii) evaluate alternatives using the above decision making protocol iv) select a preferred alternative	A preferred restoration program
11. Detailed Design Phase	I) watershed based level of analysis: if a reference channel(s) are available then employ a conceptual/empirical based approach to derive a surrogate channel; otherwise, use a conceptual/empirical/physically process based approach to design a surrogate channel ii) reach level analysis: refine approximation of surrogate channel by balancing planimetric, hydraulic geometry, friction and excess boundary shear stress estimates with sediment transport capacity at bankfull stage	Design drawings and specifications

	iii) develop the project channel by refining the hydraulics of the local varied flow geometry using flow net approximations	

16.3.1 STEP 1: Is The Channel Within The Expected Range Of Variance?

Most restoration projects begin with the identification of a perceived problem and a need for the assessment and possible implementation of corrective measures. An example may be the threat of structural damage to a home by the retreat of a river bank. Erosion of the bank may be associated with:

i) the natural migration tendencies of a stable stream channel system;
ii) an isolated, episodic event such as the diversion of the channel by a debris dam either due to Large Woody Debris (LWD) or possibly the catastrophic failure of a floodplain embankment in an otherwise stable channel system;
iii) accelerated geomorphic activity and channel alteration associated with urbanization; and,
iv) some combination of the above.

In case i) the perceived problem is the migration of the channel rather than the location of the structure. Mitigation may involve relocation of the structure if practical and feasible or localized bank restoration measures. In case ii) removal of the obstruction and localized bank stabilization measures may effectively mitigate the problem. In case iii) localized bank protection measures are unlikely to be successful if the progressive alteration of the stream channel toward a new equilibrium position is not addressed in the development of the remediation strategy. In each case the nature of the proposed solution is unique to the causative factor(s) and the associated morphologic response of the stream channel. Consequently, the objective of this component of the protocol is to assess, at a preliminary level, the spatial and temporal scale of the perceived problem and the sensitivity of the system to possible perturbations in the factors controlling the form of the channel system.

This can be done using parallel corroborative approaches to establish the existing and pre-disturbance state of the stream channel using (a) a desk-top analysis of available information, and (b) a synoptic level survey of the watershed and the channel system. The synoptic level survey is used to establish the geomorphic stability of the channel system and its mode of adjustment in its current state. A Rapid Geomorphic Assessment (RGA) approach (see Section 9.0) has been developed for this purpose. The degree of impact of any disturbance can be assessed through reconstruction of the morphology of the pre-disturbance channel. Sources of information include: a review of historic aerial and oblique photographs; an analysis of historic, existing and future land use mapping; an assessment of physiographic and topographic mapping; a review of historic channel modifications based on engineering drawings; interviews with residents and municipal staff to obtain personal accounts; a trend analyses of flow time series available from flow gauging stations; previous reports; and, estimates of the hydraulic geometry of the stream through the project reach using empirical relations based on regional data . These may be combined with the observations recorded on the RGA form and theoretical models of channel adjustment to reconstruct the historic channel.

16.3.2 STEP 2: Principle Factors Responsible For The Alteration Of Channel Form

Flow rate has been identified as the principle factor controlling channel cross-sectional area while sediment loading from the production zone has been found to provide a modifying function (Richards, 1987; Osterkamp, 1979). They also noted that within the stream itself, bank material composition and riparian vegetation are the key factors controlling and modifying channel form respectively. Consequently, the purpose of this Step is to define the nature of the change to the causative factors or driving mechanisms controlling channel form.

In the case of urban development within a watershed, Booth and Jackson (1994) noted that a change in basin imperviousness of approximately 10% may result in the de-stabilization of the stream channel as measured by hydraulic geometry parameters. Morisawa and Laflure (1979) report similar findings in that streams begin to adjust their hydraulic geometry when approximately 25% of basin area achieves an imperviousness of greater then 5 percent. A synthesis of the use of imperviousness as a surrogate for instream erosion potential and habitat degradation has also been presented by Schueler (1995). Consequently, land use maps showing the change in % impervious cover over a watershed can be used to assess the change in the driving mechanisms. Other factors, such as diversions, instream works, alteration of riparian vegetation, major landslides, forest harvesting, forest fires, knick point migration, etc., should be noted during the synoptic level survey or determined from the review of historic information.

16.3.3 STEP 3: Historic Channel Morphology

The emphasis in Step 1 was identification of the problem and its magnitude. The same data base is used here to refine the estimate of planimetric and hydraulic geometry of the historic channel system. It may be necessary to use paleofluvial techniques, such as tree coring and the interpretation of borehole data and excavation pits as well as a mapping of fluvial features, to reconstruct the long term history of the site if multiple impacts have occurred over a long period of time. An example may be deforestation followed by active cultivation giving way to scrub lands and subsequent urbanization over a period of two hundred years. Given the relaxation time for planimetric form adjustment may be of 10^2 to 10^3 years, it is possible that the current disturbance is being superimposed over the impact of previous land use changes.

Again a corroborative parallel approach to the reconstruction of the historic channel is suggested. Techniques include:

i) use of empirical relations developed from regional data bases;
ii) historic engineering drawings for diversions, road crossings, sewer outfalls, pipeline crossings, and so on;
iii) hindcasting using empirical relations such as Morisawa and Laflure's (1979) channel enlargement curve;
iv) interpretation of historic aerial photographs and other historical documentation;
v) personal accounts; and,
vi) paleofluvial field investigations (if required these investigations will be undertaken under Step

5 as described below).

16.3.4 STEP 4: Anticipated Perturbations In The Fluvial System

Site specific works will be impacted by the processes operating within the system as a whole and the state of adjustment of the system to these processes. Consequently, the current state of adjustment of the system, its sensitivity to an alteration in the driving mechanisms and any anticipated alterations in these mechanisms must be assessed. Step 1 involved a synoptic level survey using the RGA form which provides a basis for the assessment of the current state of the channel at selected locations. This survey, while not exhaustive, can be combined with other data sources (such as aerial photography), to identified major disturbances in the system and provide a context for the interpretation of future impacts on channel form. An example would be the propagation of a sediment wave through the channel system associated with a landslide. The periodicity of the wave may be measured in tens of years and channel morphology may or may not return to the pre-disturbance state after passage of the wave through the system. Consequently, location of the wave relative to the reach of interest and the potential impact on the morphology of the site must be determined before anticipated impacts associated with other disturbances, e.g. urban development, can be assessed.

Other potential impacts can be identified from future land use maps or planned modifications to the flow network. Alteration of the sediment-flow regime associated with these changes must also be addressed in the development of the restoration program.

16.3.5 STEP 5: Field Program

In order to determine how the channel will respond to these anticipated disturbances in the fluvial system a detailed field program is required to characterize channel morphology, geomorphic processes and sensitivity to alteration in the sediment-flow regime. This is achieved through integrated biotic, engineering, geomorphic and geodetic surveys of the project reach(s). Although the biotic and engineering components are fundamental to the development of the restoration plan, for the sake of brevity, only the geodetic and geomorphic surveys are described here.

The geodetic survey includes a longitudinal profile (along the channel centerline and thalweg) and detailed cross-sections through the project reach(s). The cross-sections should be taken perpendicular to the channel at the cross-over points on riffle elements and through the meander apex. The geomorphic survey includes: the characterization of bank materials at each cross-section on the basis of stratigraphic unit and their sensitivity to scour; the characterization of substrate and substratum in terms of susceptibility to scour; the description of riparian vegetation as measured by type, density, distribution and root zone depth; flow rate and estimates of hydraulic variables; a mapping of planimetric forms; a classification of channel stability; observations noting the evidence of the principle processes controlling channel form.

Geotechnical data regarding slope stability may also be required as well as information for paleogeomorphic investigations. These investigations share common data sources dealing with evidence and characterization of historic mass failures and slope processes.

16.3.6 STEP 6: Channel Response To Past and Anticipated Perturbations

The purpose of this analyses is to establish the amount of channel alteration which has already occurred and quantify the amount of impact expected to occur. There are both empirical and deterministic approaches which may be applied for this purpose.

Calibrated, deterministic hydrologic simulation model(s) can be employed to recreate the historical flow series and estimate changes to the flow regime based on future land use and flow network alterations. These models can be coupled with algorithms of instream erosion potential to provide a more direct measure of the potential impact of past and future alterations to the driving mechanisms. These approaches include both 1-dimensional (hydrologic and mass balance) and 2-dimensional (mass balance) approaches. The hydrologic approach is based on flow exceedance and duration concepts while the mass balance approach is based on threshold and dynamic equilibrium concepts.

Other techniques include bivariate and multi-variate empirical models can also be applied. Bivariate models, such as hydraulic geometry relations, should be used with caution in unstable channel systems which may tend toward a new equilibrium position an a fundamentally different form. The Morisawa Laflure (1979) enlargement curve is a bivariate model in its current form. The revised enlargement curve may be considered to be a multi-variate model.

16.3.7 STEP 7: Can The Perturbations Be Controlled At Source?

The principle factors causing instability within the project reach and the magnitude of the anticipate impact have been identified in the previous Steps. In planning the mitigative strategy one of the first considerations is the control of the source of the disturbance. Where the disturbance is local, e.g. a scour hole at the outlet from a storm sewer system, control of storm flows from the urban area may be impractical and the mitigative strategy may be to undertake localized instream works. As the spatial scale of the impact increases, mitigation strategies which deal with the source of the disturbance become more viable. In the case of existing urban development, assuming traditional development forms and storm drainage practices, opportunities may exist for the retrofit of flood control structures or the implementation of source controls (cisterns, grass swales, disconnection of downspouts, etc.). Mitigation measures for future developments include both retention (volume control) and detention (rate control) BMP measures. An SWM Policy of 'no net increase in instream erosion potential' may be considered as the basis for design of these facilities.

16.3.8 STEP 8: Justification For Intervention

Conceptual geomorphic models can be used to predict the configuration of the ultimate, stable channel form resulting from perturbations in the driving mechanisms. Based on these models the impact of channel alteration on socio-economic and environmental factors can be assessed. For example, a rock bed channel with a veneer of alluvium which has developed a stable pool-riffle morphology and self sustaining fish community may scour down to bedrock resulting in the loss of habitat value, exposure of pipelines and loss of riparian vegetation, damage to riparian structures and loss of property. If these impacts are determined to be unacceptable in accordance with established protocols, then a recommendation to proceed with the development and implementation of a restoration program may be advanced to decision makers. The key to this aspect of the management system is that a decision support algorithm be in place to provide a framework to provide guidance for application of the technical program.

16.3.9 STEP 9: Mitigation Strategies

The development of a mitigation strategy is tied to the causative factors and the *Type* of restoration program required. In the context of urban development, a number of instream mitigation strategies can be formulated including a do-nothing alternative, traditional hardlining of the channel, 'natural' channel design, and Geomorphic Referenced River Engineering (GRRE). Each of these alternatives may be applicable along the length of a particular stream depending upon the degree of current impact, relevance and anticipated degree of success of source controls, the applicability and effectiveness of centralized controls, the degree confinement and encroachment of existing structures and utilities, the significance of the environment attributes within the channel system, and available financing. For example, the urban core through the lower portion of a basin may represent a buildout area with a high degree of encroachment on the floodplain and active channel system. The active channel may be channelized over much of its length and the degree of anticipated enlargement may be relatively small. Further, financial constraints may preclude removal of these structures and flood hazard priorities may limit the potential for the 'naturalization' of the stream channel system through this reach. In this case a do-nothing option or minor habitat enhancement program coupled with upstream sediment stabilization programs may be considered as the only practical alternative over the short run. A floodplain acquisition program may be considered as part of a long term plan.

Following the same scenario, the middle portion of the basin may be in residential land use and setback out of the floodplain. The active channel, however, may be spanned in numerous locations by road and pipeline crossings and storm sewer discharges may have contribute to the de-stabilization of the channel system. Although the channel morphology may be undergoing active adjustment, a significant amount of channel enlargement is still anticipated. In selecting the mitigation strategy the instream structures place limits on the degree of active channel migration which can occur without significant potential impact and maintenance costs. In order to restore the habitat and aesthetic value to the stream and protect existing structures, a GRRE approach combined with the re-design/location of selected structures and retrofit SWM measures may be applicable. The GRRE approach attempts to emulate the form and function of a 'natural', stable stream channel system specific to the region while minimizing the ability of the channel to migrate. This approach typically involves the armoring of the bed and bank toe and the application of soil bioengineering in the mid and upper bank areas in a manner that emulates a natural system in that: it maintains a the step-pool or riffle-pool morphology, bed material composition and planimetric and cross-sectional form consistent with streams within the region; it meets fisheries habitat morphometric targets; it has a dense riparian vegetation cover; and, it is in dynamic equilibrium in that sediment mass entering the project reach equals the export of sediment from the reach.

In the upper portion of the watershed the lands may be under development or planned for development. Mitigation measures may include 'naturalization' of the impacted stream reaches and preservation or enhancement of existing stable reaches. The later objective may be attained through the implementation of suitable SWM controls in new developments and retrofit options in existing developments.

16.3.10 STEP 10: Preferred Restoration Program

The recommended approach is selected according to an accepted framework for decision making. An example of a decision making protocol is provided in Table 16.5.

16.3.11 STEP 11: Detailed Design Phase

Case studies have shown that the response of the active channel to a disturbance in the driving mechanisms controlling channel form vary significantly due to differences in the streams susceptibility to a change, the magnitude and temporal and spatial characteristics describing the perturbation in the driving mechanisms, the time elapsed from occurrence of the disturbance, the relaxation time of the fluvial features of interest and the state of equilibrium of the channel with respect to historic disturbances. Consequently, each design is highly site specific. Fortunately, stream channel systems have a certain degree of flexibility and the design does not have to be exact but within an acceptable range of tolerance.

Table 16.5. Factors/Indices For Alternative Assessment/Selection

FACTOR	INDEX	CRITERIA
ENGINEERING ENVIRONMENT	Feasibility/Practicality	Machinery accessible/legal access
	Existing Utilities	No disruption to sanitary trunk sewer or pedestrian/bicycle pathway/bridge structures, etc.
	Flood Hazard	Zero increase in regulatory year flood line
PHYSICAL ENVIRONMENT	Aquatic Habitat	Net increase in habitat value-length / 50% of riffle material mobile less then 30% of time on annual basis /
	Terrestrial Habitat	Net increase in riparian habitat/minimize loss of existing hardwood stands
	Stream Morphology	intact channel boundary materials stable at bankfull stage / channel position is fixed in time and space
SOCIAL ENVIRONMENT	Aesthetic Value	Maximize natural appearance
	Accessibility	Provide public access at selected locations
	Land Ownership	Improvements are restricted to public lands
FINANCIAL ENVIRONMENT	Capital Cost	Minimize cost within above constraints
	Maintenance Cost	Minimize cost
	Safety	Minimize public risk

The objective of the designer is to determine a morphology which is within this range of tolerance and allow the stream to do the final adjustments. Through a general understanding of the physical laws governing channel behavior and a combination of empirical and physically based relations, and professional judgment, a detailed design of the channel can be prepared. The degree to which empiricism, physically based models and professional judgment are employed will depend upon the nature of problem. For example, a *Type* 1 restoration approach involving disruption of the channel due to alteration of the riparian vegetation, may employ the use of empirical models based on observations gathered from a similar reach upstream of the subject site. In contrast, an urban system which is unstable and experiencing a high rate of geomorphic activity over much of its length may require more reliance on physically based models and a conceptual understanding of the evolution of channel form.

Potential General Recommendations

An example of generalized recommendations that can be applied to many watersheds is listed below and based on the findings in the Williamson Creek Watershed Erosion Assessment.

Review of field reconnaissance data and computations for Williamson Creek and its major tributaries, prompted the discussion of potential management approaches that could be implemented at a particular location, reach, or entire length of the channel. Following is a list of management approaches and a brief discussion on the application to Williamson Creek.

Items to be considered in the development of a management plan for each watershed include:

1. Develop design guidelines to verify management of the bankfull flow by water quality control ponds that are constructed with new development. Computation of the typical bankfull flow storm event (3-month, 6-month, 1-year, etc.) should be performed and routed through the water quality pond to calculate the detention benefits of these facilities. Baseflow enhancement is an added benefit due to the release of stormwater flow over an extended period.
2. Detention pond retrofits should be investigated at existing regional and large private detention ponds. The Scenic Brook and Dick Nichols Park pond are likely candidates for retrofit. Bankfull flow channel design should be a design feature of all regional detention ponds.
3. Limiting new impervious cover and connected impervious cover through regulation or incentives will minimize the impact of the hydrologic component that most influences the enlargement of the channel. Landscaping requirements and buffers would be a means to disconnect impervious areas. Coordination with other City departments to determine the necessity of sidewalks on both sides of the street could result in the significant reduction of impervious area with new development. Other technologies such as grass "paving" for low use and remote parking lots could be used in commercial areas to reduce peak runoff rates and volumes.
4. Channel engineering to manage the widening and plan form changes could be implemented in problem areas to protect threatened areas and reduce the sediment load to receiving water bodies. By excavating the bankfull flow channel to the desired future condition and creating a floodplain capable of conveying flood flows will minimize the sediment transport from one reach to the next.
5. Implementation of an inspection and maintenance program that removes fallen trees, clears excessive vegetation in the floodplain, and repairs isolated erosion problems will assist the channel in conveying increasing flow rates in the developing watershed. Creating improved conveyance in the floodplain minimizes the pressure of the channel to convey the majority of stormwater during flood events. Now the floodplain can perform the role of flood flow conveyance.
6. No management action and allow the channel to evolve in response to changes in the watershed will lead to the loss of channel banks, trees, property, and structures. This approach may have the least up-front cost, but expenses in the future to protect structures and property may exceed the costs of a planned channel management program.
7. Acquisition of additional parkland along the creek and floodplain corridor in one effort will allow the City to implement management programs in the future without the requirement of obtaining easements for individual programs. A hike and bike trail greenway could be implemented in conjunction with creek management approaches. However, several residents we met during the

stream inventory indicated that a hike and bike trail was not desired along the creek for security, environmental, and quality of life reasons.

8. Investigate the potential of planned regional detention ponds to provide detention and hydrograph management for frequent storm events.
9. Determine the location of major storm drain outfalls from highly developed areas and their potential for retrofit. The detention pond retrofit could be located within the 100-year floodplain of the receiving stream, thus reducing land acquisition costs and floodplain modifications.

Output

A table similar to the following will be included in each watershed assessment report to indicate an appropriate response to the existing stream problems. Also, recommendations will be provided on a reach by reach basis.

TABLE 12-1

CHANNEL EROSION MANAGEMENT RECOMMENDATIONS

WATERSHED ID	FIRST LEVEL TRIB.	SECOND LEVEL TRIB.	REACH NUMBER	REACH LOCATION	STREAM TYPE	CURRENT CONDITION	REACH LENGTH (feet)	REACH SLOPE (%)	EXISTING % IMPERVIOUS COVER (%)	FUTURE % IMPERVIOUS COVER (%)	SEDIMENT YIELD PER LINEAR FOOT (tons / L.F.)	EXISTING LAND USE, CURRENT R_E	FUTURE LAND USE, ULTIMATE R_E	FUTURE R_E/ CURRENT R_E
	Fort Branch													
FOR	000	000	01	From confluence with Boggy Creek to MKT Railroad.	Alluvial	In Adjustment	600	0.67	43.4	50.7	3.68	4.7	7.0	1.49
FOR	000	000	02	From MKT Railroad to Webberville Rd.	Rock Bed	In Adjustment	9,220	0.50	45.2	50.4	3.50	2.7	3.5	1.28
FOR	000	000	03	From Webberville Rd. to Springdale Rd.	Alluvial	In Adjustment	4,580	0.83	48.4	50.0	1.22	5.9	6.9	1.17
FOR	000	000	04	From Springdale Rd. to Manor Rd.	Rock Bed	In Adjustment	5,560	0.72	53.8	54.0	0.18	7.3	7.9	1.08
FOR	000	000	05	From Manor Rd. to Tributary at Westminster Dr. and Waterbrook	Alluvial	In Adjustment	2,500	0.72	55.5	56.1	0.48	7.5	8.2	1.09
FOR	000	000	06	From Tributary at Westminster Dr. and Waterbrook Dr. to	Structural	Stable	1,750	1.14	58.7	60.5	0.00	2.9	3.2	1.10
FOR	000	000	07	From Rogge Ln. to150 ft. D'S Berkman Dr.	Alluvial	In Transition (Stressed)	1,550	1.29	61	63.2	0.29	8.6	9.8	1.13
FOR	000	000	08	From 150 ft. D/S Berkman Dr. to 550 ft. D/S Glencrest Dr.	Structural	In Transition (Stressed)	2,200	1.00	67.3	70.0	0.05	3.4	3.8	1.12
FOR	000	000	09	From 550 ft. D/S Glencrest Dr. to U.S. 290	Alluvial	In Transition (Stressed)	1,350	1.04	69.2	73.3	0.09	9.5	10.1	1.06
				Tributary										
FOR	T01	000	01	From confluence with Fort Branch to Wheless Ln.	Alluvial	In Transition (Stressed)	3,850	0.62	40.6	44.8	0.49	3.9	5.5	1.43

TABLE 12-1

CHANNEL EROSION MANAGEMENT RECOMMENDATIONS

	Fort Branch					
WATERSHED ID	FIRST LEVEL TRIB.	SECOND LEVEL TRIB.	REACH NUMBER	PRIORITIZATION SYSTEM RANK SCORE	RECOMMENDED MANAGEMENT APPROACH	MANAGEMENT SPECIFICS
FOR	000	000	01	12.8	Type 2	Due to channelization upstream, severe erosion is expected throughout reach. Construct future active channel per estimated future enlargement. Protect side slopes to prevent occurance of steep unstable slopes.
FOR	000	000	02	76.6	Type 2	Due to channelization upstream, severe erosion is expected throughout reach. Construct future active channel per estimated future enlargement. Stablize steep slopes throughout reach using natural design guidelines.
FOR	000	000	03	38.7	Type 2	Previous erosion has left very steep unstable slopes. Future channel erosion may cause large sediment losses due to the existing slope problems. Stabilze and reduce steepness of slope using natural design guidleines.
FOR	000	000	04	10.0	Type 1	Channel has nearly reached it's ultimate channel size and very little further erosion is expected. Manage Localized disturbances. Bank protection may be constructed at certain locations with steep unstable slopes using natural design guidelines.
FOR	000	000	05	100.0	Type 2	Throughout reach channel has steep unstable slopes and several Type 2 and Type 3 sites. Although the channel is near it's ultimate size, the steep unstable slopes may result in future erosion. Construct bank protection along the steep slopes
						throughout the reach using natural design guidelines.
FOR	000	000	06	0.0	Type 1	Structural channel with no major problems. Manage localized disturbances.
FOR	000	000	07	1.6	Type 2	Channel has nearly reached it's ultimate channel size and is in good shape with few major erosion problems. However home owner at Rogge lane complains that his yard and house gets flooded several times per year and suspects the
						culverts at Rogge Lane are undersized. There is backwater upstream of the bridge at Rogge Lane which may reduce the effective channel capacity.
FOR	000	000	08	1.0	Type 1	Structural channel with no major erosion problems. Some siltation has occured and this will need to be maintained to prevent large growth that will reduce channel capacity. Manage localized disturbances.
FOR	000	000	09	6.7	Type 1	Little future erosion expected. Future channel improvements in this reach will further reduce estimated enlargement. Manage localized disturbances.
FOR	T01	000	01	16.8	Type 2	Channel has several locations with steep unstable slopes which will contribute more sediment loss than estimated. Construct future active channel per estimated enlargement. Stabilize slopes using natural design guidelines where possible.

17.0 WATERSHED MAPPING

Purpose

To identify the location of erosion areas, like reaches, photograph locations, rock outcrops, geomorphic cross sections, knick points, and other data, strip maps will be prepared for the studied stream length of each creek and their significant tributaries. The maps will be based upon the City of Austin 1"=200' topographic maps. Noted on the maps are wastewater lines in the creek, storm sewer outfall locations, channel improvements, and springs and seeps, that will be identified during the field reconnaissance. Photographs of the above features will be noted on the maps and discussion is included in Section 18.0 of this text.

Approach

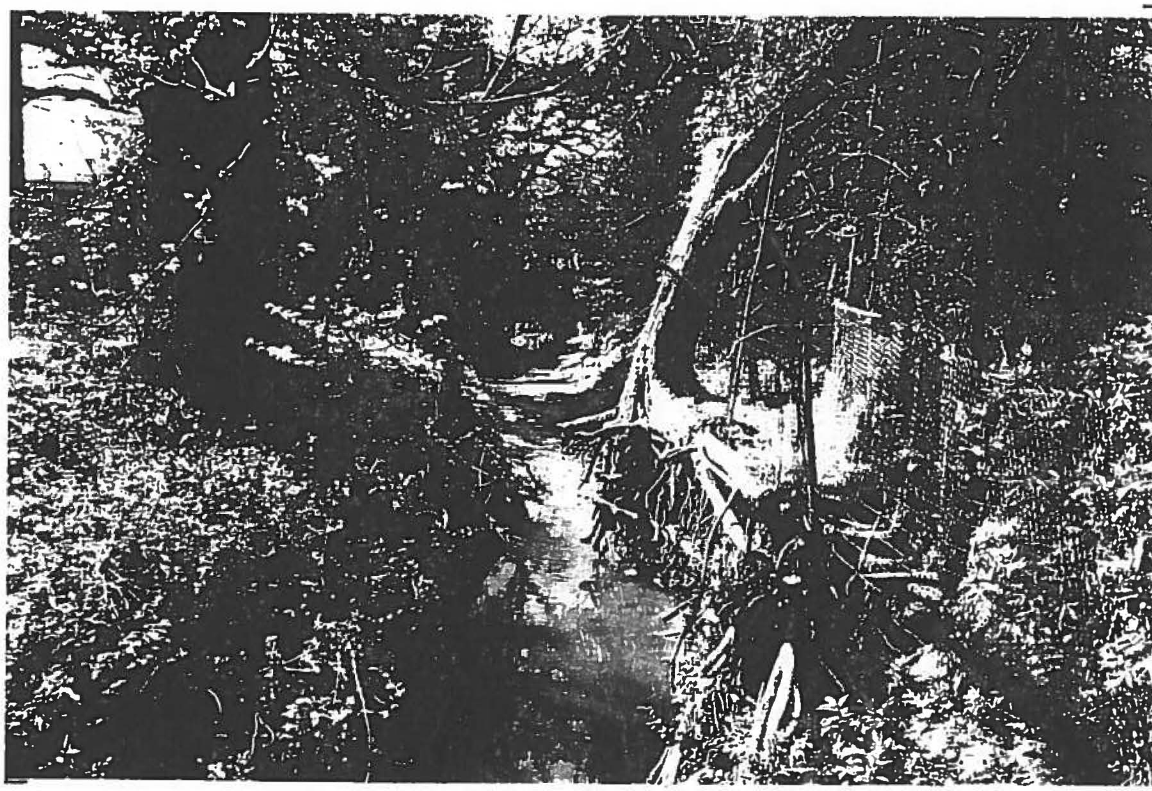
From City of Austin provided 1"=200' topographic maps, most of which are based on late 1970's aerial photogrammetry, maps will generated to depict the above referenced features. In addition, review of the 1987 planimetric maps was performed to update the topographic maps. The maps were used during the stream inventory as a working field map to locate identified features and their relation to existing structures. This allowed an accurate placement of the identified erosion problem or geomorphic feature.

In addition, data from the 1"=200' maps was transposed onto USGS based maps and provided to the City of Austin for input into the Drainage Utility's GIS mapping data base. This will allow the production of color maps on a watershed scale for presentation and watershed planning purposes.

Output

See the attached figure for an example of the watershed mapping at a scale of 1"=200'. The Drainage Utility is presently preparing watershed maps and a copy of a completed map will be included in each report.

Roll 11, Exp. 21. Looking upstream through section.



Roll 11 Exp. 22. Located upstream of section looking upstream.

EAST BOULDIN CREEK
CROSS-SECTION 60

CITY WIDE WATERSHED EROSION ASSESSMENTS
CITY OF AUSTIN
TRAVIS COUNTY, TEXAS

RAYMOND CHAN & ASSOCIATES, INC.
CONSULTING CIVIL ENGINEERS

1102 WEST AVENUE ♦ AUSTIN, TEXAS 78701
OFFICE: (512) 480-8155 ♦ FAX: (512) 480-8811

SHEET 1 OF 2	DATE: 03/13/97	JOB : 225

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20.0 GLOSSARY

$(D_{BFL})_{ACT}$ - Depth bankfull, active channel.

ϕ_{75} - The diameter (in millimeters) of sediment particle size measured along a representative transect of a channel section for which 75% of material by mass is smaller.

ϕ_g - The geometric mean of diameters (in millimeters) of individual particle sizes measured along a representative channel transect.

Active Channel - That portion of a channel that is formed by geomorphically significant flows.

Aggradation - A modification of a channel in the direction of uniformity of grade by deposition.

Alluvium - Sediment deposited by moving water.

Armoring - A protective covering composed of a erosion resistant material along the channel surface which forms a resistant barrier to erosion due to elevated flow velocities.

Bankfull Depth - Water depth that corresponds to a specified region of a channel including top of bank (above which lateral flows are not contained in the channel), active channel (see Active Channel), and inset channel (see Inset Channel).

Boundary Material - Rock, alluvium, undisturbed overburden, or fill material which forms the surface layer along the channel bed and/or banks.

Channel Enlargement Factor - A factor by which the pre-developed channel effective flow area is enlarged to simulate the future developed conditions (see "Enlargement Ratio").

Channelization Works - Construction activities modifying the channel shape, pattern and profile.

Degradation - Erosion resulting in loss of channel material such that the channel form is significantly altered. This may result in the destabilization of existing structures such as bridge piers and storm sewer outfalls.

Diagnostic Survey - Field observations of geomorphic characteristics in the channel including soil consistency, bank material composition and environmental integrity. This is more rigorous than a "Synoptic Survey" and less rigorous than a "Detailed Geomorphic Survey".

Effective Flows - Those flows rates having the greatest effect on channel form in terms of frequency of floods, flow depths and velocities.

Enlargement Ratio - A factor derived from the geomorphic survey based on impervious cover. Used to estimate the channel enlargement by multiplying times the active channel bankfull area.

Enlargement Curve - A graphic representation that compares the percentage of total impervious cover (TIMP) to a predicted channel enlargement ratio (determined by empirical methods) as a function of stream type.

Fluvial Sediments - Deposits formed on land from the sediment load carried by moving water.

Geometrically Corrected Channel Area - An extrapolation of a channel cross-sectional shape (extending either forward or backward in time) which is dictated by the channel material which affects the relative rates of vertical and/or horizontal enlargement due to erosion.

Geomorphically Significant Flows - See "Effective Flows".

Geomorphology - The study of landforms (for this study, those affected by channelized flows), including the description, classification, origin, development, and history of surface features.

Historic Channel - The channel cross-sectional shape (defined in this study) as that recorded in as-built design drawings of sanitary sewer line profiles at stream crossings.

Hydraulic Geometry - Those parameters of channel cross-sectional and longitudinal shape used to evaluate channel flows, velocities and depth of flow. Parameters include wetted perimeter, cross-sectional flow area, hydraulic radius, Mannings roughness coefficient, and channel slope.

Hydraulic Radius - The ratio of the channel cross-sectional flow area to the wetted perimeter. One of the parameters of hydraulic geometry used to determine flow characteristics.

Infilling - The process of deposition of fluvial material which fills a portion of the channel cross-sectional area.

Inset Channel - A small conveyance channel formed by flows during low frequency (less than 1 year return periods) storm events.

Mannings Roughness Coefficient (n) - A measure of surface roughness in the channel. It is one of the parameters used to determine hydraulic flow characteristics.

Mesoform Relaxation Periods - The amount of time required for a channel to finish responding (through enlargement) to increased erosive forces caused by increased development in the upper contributing drainage area.

Planimetric Adjustment - Channel changes its pattern in plan form.

Priority Erosion Sites - Roads, bridges, buildings currently threatened by channel erosion.

Rapid Geomorphic Assessment - Form used to identify channel adjustment processes to label a reach as stable, in transition (stressed) or in adjustment.

R_E - See Enlargement Ratio

Reach - A channel segment with similar geology and morphology.

Recurrence Interval - Storm event frequency such as the 2-year storm.

Relaxation Period - The period of time for the channel to fully adjust to an upstream watershed or channel disturbances.

RI, See recurrence interval

Riparian Vegetation - Plants, trees, etc. along the stream channel and floodplain.

Rock-Controlled - The channel bottom and side slopes are composed of rock.

Stream Type - A classification of channel composition features which affect the lateral and vertical direction of channel enlargement due to erosion. See "Rock Controlled Channel,

Rock Bed Controlled Channel and Alluvial Channel."

Stability Index - A number used to predict changes in channel morphology determined by tallying geomorphic indicators from a defined list of 32 indicators which qualify aggradation, degradation, channel widening, and planimetric adjustment.

Synoptic Survey - An overview of channel reach conditions determined by a quality based on-site observation of the channel.

Thalweg - The centerline of the channel at the lowest elevation point of channelized flow at a specified cross-section.

Theoretical Relaxation Period Correction Factor ($R_E/R_{E(MAX)}$) - The ratio of the channel enlargement ratio at a specified time after development occurs to that estimated for the ultimate channel enlargement under fully developed watershed conditions. This value can be used to estimate the percent of ultimate enlargement that will occur at a specified time following development of a contributing drainage area.

t_i - Average age of development.

TIMP - % of total potential impervious cover.

Valley Formation - Channel downcutting and widening causing reconstruction of the entire stream valley at a lower elevation.

Weighted Age of Development - The average age of development in each watershed.

Wetted Perimeter - In cross section, the channel surface length experiencing flow for a particular storm.

WWL - Wastewater Line

{ [(ABFL) INS] PRE } CUR
DBFL ACT HIS ULT
TER EXT
TOB FUT

ABFL - Area bankfull
DBFL - Depth bankfull
INS - Inset channel
ACT - Active channel
TER - Terrace
TOB - Top of bank
PRE - Pre development
HIS - Historic (data of wastewater line construction for geomorphic survey)
EXT - 1997
FUT - Future
CUR - Current condition
ULT - Ultimate channel condition including relaxation.